



Coastal Ocean Processes: A Science Prospectus

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by

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April, 1992

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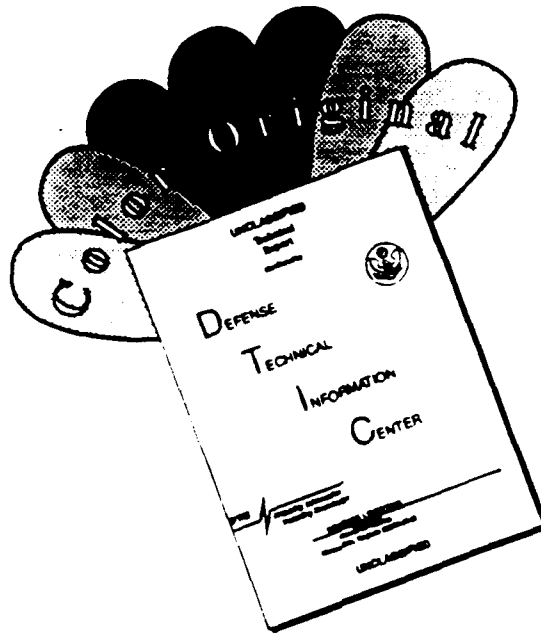
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by

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Technical Report

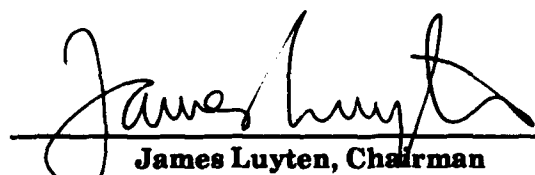
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Foreward

The Ocean Sciences Division of the National Science Foundation (NSF) has funded since 1987 a planning activity to draw the academic coastal ocean science community toward consensus on the priorities for coastal zone research over the next decade.

Societal interest in coastal waters has always been high, but increasing migration to coastal communities raises complex public policy issues ever more frequently. Long-term continuing concerns, such as efficient husbandry of natural resources and preservation of environmental quality, are augmented by local problems that range from localized fish kills to the appearance of medical waste on beaches. Understanding the coastal ocean can lead to mitigation or prevention of chronic problems or short-term crises. This understanding probably depends ultimately on relatively few fundamental scientific principles that govern how the coastal ocean works, and how it interacts with processes both landward and farther offshore.

The coastal ocean, as defined for the purposes of this report, looks outwards from the shoreline beyond the river mouth and tidal wetland edge. It includes large enclosed or semi-enclosed bodies of water such as the Great Lakes, Chesapeake Bay and Puget sound. On the shoreward side, important processes couple the coastal ocean to the terrestrial landscape through water flow via watersheds and river estuaries, wetlands, groundwater, and so forth. Within NSF these are the subject of a complementary Land Margins Ecosystem program, a combined effort of the Ocean Sciences and Environmental Biology divisions.

It is the basic responsibility of NSF and academic scientists to work together to provide the resources and intellectual capacity to gain scientific knowledge that can be incorporated into actions by other federal as well as state and local agencies.

We see this Science Plan as a major contribution to (1) the identification of the underlying science questions and (2) the ongoing deliberations of the Subcommittee on U.S. Coastal Ocean Science of the Committee on Earth and Environmental Sciences of the Federal Coordinating Council for Science, Engineering and Technology.

The Ocean Sciences Division of NSF wishes to thank Dr. Kenneth Brink, Chairman of the Coastal Ocean Processes Steering Committee, and members past and present, for their exceptional and sustained efforts in the production of this chart of current needs for future understanding and prediction.

Dr. Michael Reeve
Section Head, Ocean Sciences Research Section
National Science Foundation

Executive Summary

1) Coastal Ocean Processes (CoOP)

Human activity profoundly affects the coastal ocean, and coastal waters, in turn, influence the lives of the vast and increasing populations that live near them. A better understanding of this environment is imperative for reasons that range from navigation and defense needs to fisheries and weather forecasting.

Toward this end, an interdisciplinary group of coastal ocean scientists has joined together to launch CoOP (Coastal Ocean Processes). We define the coastal ocean as extending from the surf zone to the edge of the continental rise, an area generally ranging from 100 to 1000 kilometers wide and including large inland water bodies that exhibit similar processes. The coastal ocean provides a buffer between the land and the deep ocean. It is dynamically distinct and often isolated from the rest of the ocean. It harbors a number of unique physical and meteorological processes that promote high biological productivity (Figure 1), active sedimentary processes, dynamic chemical transformations and intense air-sea interaction.

Coastal ocean science has traditionally been undertaken by small groups of investigators from one or two disciplines. This approach has succeeded in studies of processes specific to a single discipline, such as tides, but has not built understanding of the complex processes that cut across traditional scientific divisions, such as toxic blooms or sediment dynamics. Although there will always be a crucial role for small groups of investigators, we believe the time is right for large-scale, fully interdisciplinary approaches to the study of the coastal ocean. CoOP therefore encompasses biological, chemical and geological oceanographers as well as marine meteorologists and physical oceanographers. This group's goal (Table 1) is:

to obtain a new level of quantitative understanding of the processes that dominate the transports, transformations and fates of biologically, chemically and geologically important matter on the continental margins.

Understanding cross-margin transport is central to achieving this goal. It links processes at work near the coast to those operating over the shelf and farther offshore.

Different processes dominate this transport near the surface, in the central water column, and near the bottom, so that we must pay close attention to each zone. These considerations helped to shape the particular CoOP objectives, to understand:

- The quantitative mechanisms, rates and consequences of **cross-margin transport** of momentum, energy, solutes, particulates and organisms.
- The **atmospheric and air-sea interaction** processes that affect biological productivity, chemical transformations and cross-margin solute and particulate transport.
- The role of transport processes that **couple the benthic and pelagic** zones of the continental margin.
- The nature, effects and fates of **terrestrial inputs** of solutes, particles and productivity in the coastal ocean.
- The **transformations** of solutes, particulates and organisms across the continental margin.

(A glossary of technical terms is provided, beginning on page 77.)

To address this set of objectives, the CoOP plan calls for an extended effort (Table 2). A sequence of process studies receives primary emphasis and gives structure to the overall CoOP effort. Each of these studies focusses on a specific coastal region where one important process dominates. Modeling studies will be integrated with the process studies and used as a means to synthesize and generalize study results. The geographical diversity of the coastal ocean is too great to allow careful measurements throughout, so the generalizing capabilities of models are crucial to the overall effort. In addition, long time-series measurements, exploratory studies, technological development, and communications (including with the applied science community) all require attention. CoOP is expected to attract support from a number of agencies having an interest in the coastal ocean sciences.

The organization of CoOP calls for scientists to initiate the major CoOP field studies; for each, one scientist will be charged with organizing a workshop to define

the specific interdisciplinary objectives and approach. The CoOP steering committee will then work with the scientist to refine the resulting plan to assure that it is well-defined, scientifically satisfying and appropriately interdisciplinary. Further, the steering committee will interact with funding agencies to help coordinate and prioritize the scientific efforts.

2) Societal Implications of Coastal Ocean Science

Practical issues make a better understanding of the coastal ocean imperative. They include (Table 3):

Anthropogenic Inputs: Humanity provides various chemical, biological and sedimentary inputs to the coastal ocean by such diverse means as sewage dumping, acid rain, agricultural land drainage and industrial wastes. At present, we know relatively little about the fates of these inputs and their net effect on the coastal ecosystem. Interdisciplinary studies of coastal ocean processes can greatly enhance this understanding and lead to reliable information for planning future activities.

Mineral Exploitation: The United States relies on numerous offshore mineral sources, especially petroleum. Offshore drilling requires information for risk assessment, structural design, and reaction to spills. Society demands ever higher standards for this information, taxing our ability to predict spill trajectories and biological impacts. Improved knowledge of physical, chemical and geological ocean processes will increase our ability to assess these risks and to react wisely to emergencies.

Navigation: Major world commerce routes cross the coastal ocean, and it is increasingly used for recreational boating. In both cases, safe, effective use of the ocean, as well as search and rescue operations, require a knowledge of sea state, over-the-water weather and currents. In addition, large vessels often require dredged channels, leading to problems in the disposal of spoils and the choice of channel routes to minimize silting. Improved knowledge of coastal meteorology, physical oceanography and sediment processes would help to improve safety and efficiency.

Recreation: In many localities, shore-based leisure use of the coastal ocean is an important source of revenue. Activities such as wildlife observation, sport fishing,

bathing and general sightseeing contribute to the attraction, yet all are sensitive to environmental quality. Understanding of the coastal ocean system can help to preserve and restore recreational resources.

Defense Needs: With decreasing cold-war tensions, but increasing potential for third world conflicts, the United States Navy is increasingly concerned with operating in coastal waters. Issues such as submarine detection (acoustic and otherwise), amphibious operations, mine warfare, biofouling and atmospheric interference with weapon system operation have gained new emphasis. Better knowledge of coastal meteorology, physical oceanography, sedimentary processes and biological oceanography would help the Navy with these defense requirements.

Fisheries: The coastal ocean provides a disproportionately large part of the world's fish catch. Effective fishery management requires understanding variations in fish stocks (both natural and anthropogenic) and maintaining a sustainable harvest. This is an extraordinarily difficult problem, requiring better understanding of physical, chemical and biological variability in the coastal ocean in order to improve the predictive capabilities of fisheries managers.

Coastal Meteorology: Humanity is affected by coastal meteorology through extreme storms, air pollution and localized patterns of fog, clouds and precipitation. Better prediction of these atmospheric conditions requires greater attention to air-sea interactions in the coastal ocean, a central focus of the CoOP effort.

The Global Carbon Cycle: Although this is essentially a scientific issue, public concern over potential climate change has made it a policy issue as well. Because so much of the world ocean's primary productivity is concentrated in the coastal ocean, we should consider its role in removing carbon from the atmosphere. At present, we do not know with certainty whether the coastal ocean is even a net source or sink of carbon from the atmosphere. Better understanding of air-sea fluxes, biological production and carbon removal from coastal waters can help to reduce our uncertainties about the fate of carbon in the coastal zone.

Coastal Hazards: Flooding and erosion of coastal lands pose major problems. Such events normally occur during severe storms (such as hurricanes), and a better understanding of coastal meteorology, surface-wave physics and sediment transport will necessarily lead to a better ability to mitigate and predict such impacts.

These considerations point to the need for a coordinated, interdisciplinary, basic-science effort in the coastal ocean. Most of the societal issues mentioned above would not be well-served by single-discipline approaches to the underlying science. Although the proposed CoOP program does not directly tackle the societal problems, it will address the underlying scientific problems that must be understood and communicated to allow applied scientists, engineers and managers to make informed practical decisions. We contend that a large part of our society's difficulty in dealing with coastal ocean problems stems from an insufficient understanding of basic processes. CoOP will contribute significantly to the needed understanding, and will thereby help to address societal issues concerning the coastal oceans.

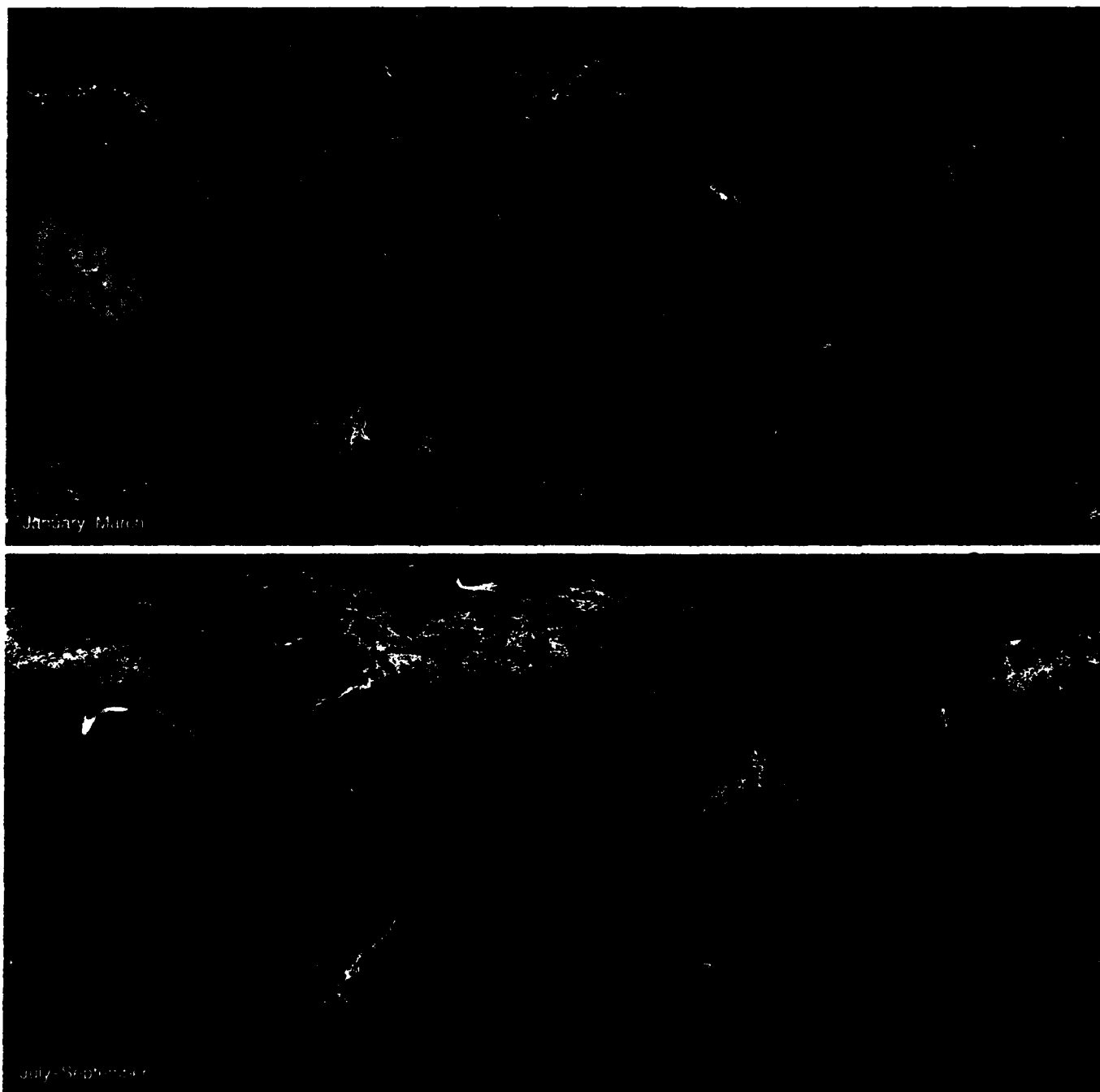


Figure 1: Coastal Zone Color Scanner (CZCS) global composite images depicting phytoplankton chlorophyll (biomass) for January-March (upper) and July-September (lower). Images show estimates of phytoplankton chlorophyll concentrations (mg m^{-3}) according to the following color scale: purple (<0.05), blue (0.05 to 0.3), green (0.3 to 0.5), yellow (0.5 to 0.9), orange (0.9 to 1.5) and red (>3.0). The images illustrate some of the important processes occurring on the ocean margins which cause increased productivity of coastal waters. For examples, note effects of: (1) coastal upwelling off the U.S. west coast (lower image), off northwest Africa (lower image) and in the Arabian Sea (lower image), (2) seasonal phytoplankton blooms in the Gulf of Alaska in response to stratification and shoaling of the upper mixed layer (compare differences between upper and lower images), (3) frontal processes at the shelfbreak off the coast of Argentina (upper image), and (4) Amazon and Orinoco River plumes (lower image) extending well into the North Atlantic and Caribbean, respectively. Images courtesy of Dr. Gene C. Feldman, NASA/Goddard Space Flight Center.

Table 1: CoOP Goals

Overall Goal:

To obtain a new level of quantitative understanding of the processes that dominate the transports, transformations and fates of biologically, chemically and geologically important matter on the continental margins.

Specific Goals:

- Cross-Margin Transports
- Air-Sea Couplings
- Seabed Fluxes
- Land-Derived Effects
- Transformations Within the Coastal Ocean

Table 2: CoOP Program Elements

- Interdisciplinary Process Studies
- Modeling
- Exploratory Studies
- Long-Term Measurements
- Remote Sensing
- Technology Innovations
- Data Quality Assurance and Archiving
- Communications
- Facilities

**Table 3: Societal Implications of Coastal Ocean
Basic Research**

- Anthropogenic Inputs: Sewage, agricultural land runoff, waste disposal, airborne particulates and gases.
- Mineral Exploitation: Risk assessment, reaction to emergencies, structural design information.
- Navigation: Sea state, winds, dredging, siltation, search, and rescue.
- Shore-based Recreation: Wildlife, swimming, fishing, sight-seeing.
- Defense Needs: Submarine warfare, mine warfare, amphibious operations, fouling, atmospheric conditions.
- Fisheries: Physical, chemical, and biological interactions.
- Coastal Meteorology: Severe storms, fog, cloudiness, air quality.
- Carbon Cycles: Inputs, processing, and fate of carbon in the coastal ocean.
- Coastal Hazards: Sea level, sea state, flooding, and erosion.

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I Introduction

A. Background

The coastal ocean ranges from the surf zone offshore to the continental shelf, slope and rise (Figure 2) and includes large inland water bodies that harbor similar processes. It is a region of the global hydrosphere that has special societal and scientific importance. Key societal issues include optimizing the utilization of renewable (e.g., fisheries) and nonrenewable (e.g., petroleum) resources while avoiding significant and irreversible harm. As more of the world's population shifts towards coastal lands, the pressures on the coastal ocean, in terms of pollution, waste disposal and recreation, continue to increase. Sensible management decisions will ultimately require greater fundamental understanding of how the coastal ocean system functions and the timely communication of this understanding to coastal managers. Advances are needed toward answering a number of critical scientific questions in order to enhance our practical understanding. These questions are exciting and complex enough to require volumes for their full treatment. However, we begin by simply listing some of the important, broad scientific issues in the coastal ocean.

1. Anthropogenic inputs

Chemical inputs can occur through the atmosphere, rivers, or groundwater. In the coastal ocean, chemicals can be consumed, transformed, or remain virtually unmodified. We need to understand the fates of pollutant chemicals and their effects on biological systems to understand the consequences of their release and to allow the development of sensible regulatory schemes.

2. Coastal ocean ecology

The coastal ocean, on a per-unit-area basis, is the most productive part of the marine environment (Figure 3). The structure of this ecosystem helps determine the fate of many of the major and minor chemical constituents that enter the coastal ocean. In turn, chemical and physical influences help to determine ecosystem structure. The overall problem is extremely complex, yet it underlies issues such as toxic blooms and fisheries management.

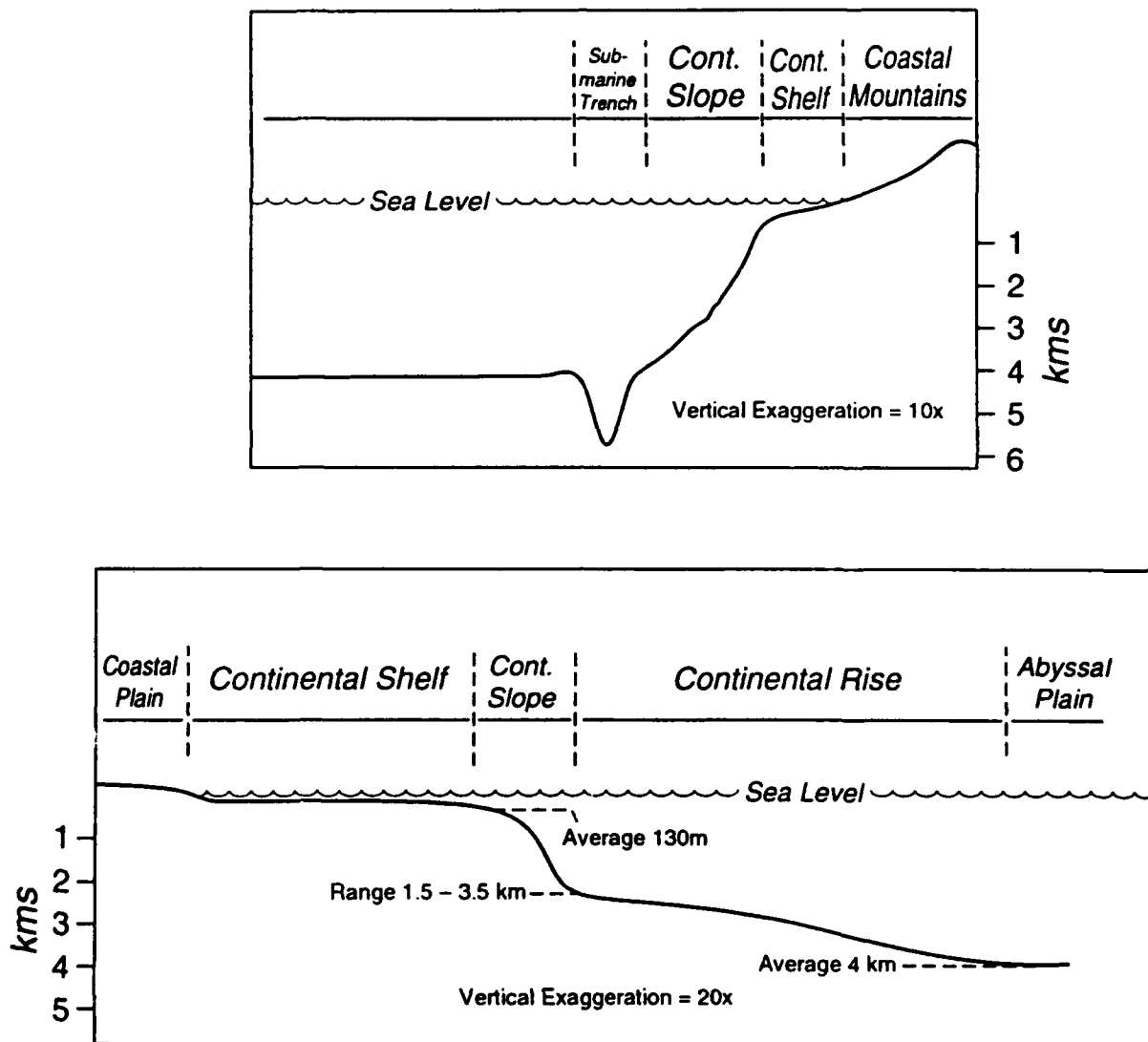


Figure 2: Typical profiles of two common types of continental margins. Upper panel: A collision margin typical of the Pacific coast of South America. The presence of a submarine trench, a narrow continental shelf, and a landward mountain range characterize this type margin. Lower panel: A trailing-edge margin typical of much of the Atlantic Ocean. The presence of a continental rise, a broad continental shelf, and a coastal plain are characteristic of this type margin.

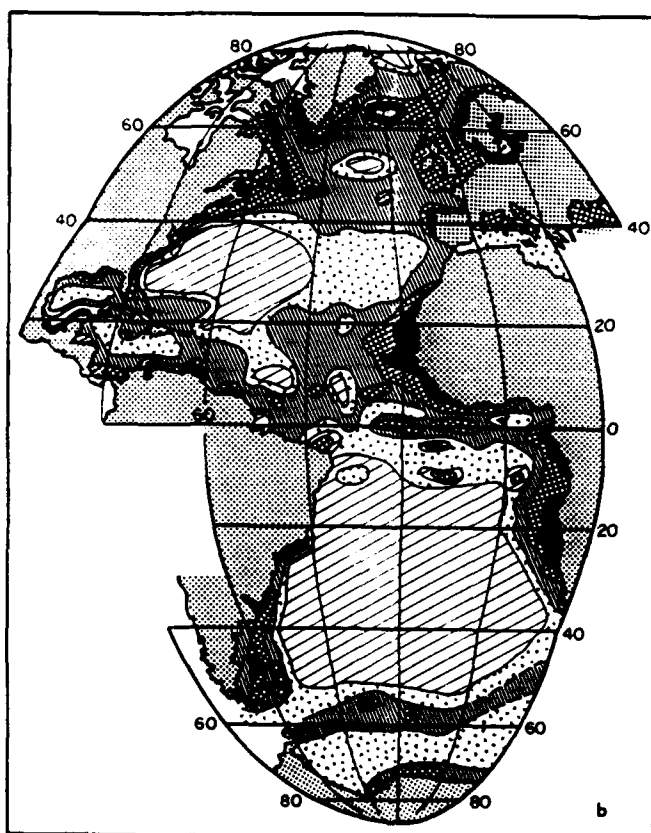
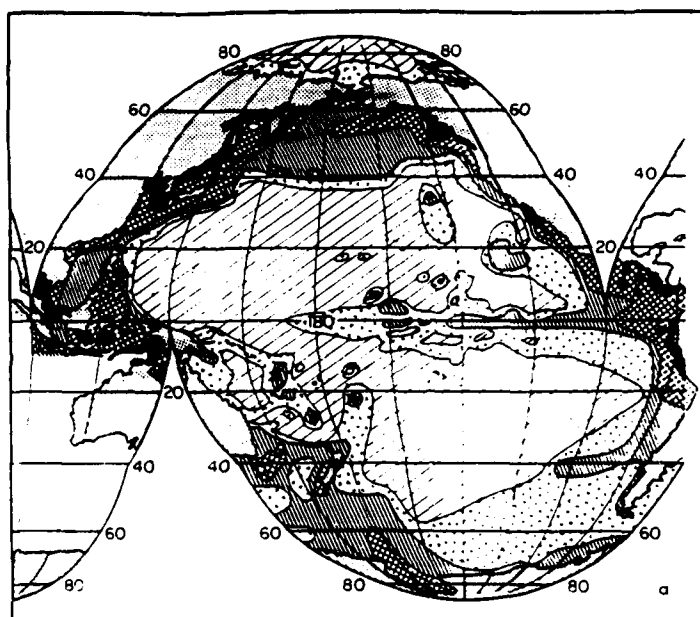


Figure 3: World ocean primary production according to Koblenz-Mishke and co-workers on an equal area projection. Productivity is in $\text{gC m}^{-2} \text{yr}^{-1}$. Categories are, from low to high, <36 , $36-54$, $54-90$, $90-180$, >180 . Note that most of the areas of high productivity are located on the ocean margins. Figure from Berger, 1988.

3. Coastal weather patterns

Certain weather patterns are unique to ocean boundaries. Examples include the land/sea breeze cycle, propagating "coastal low" weather systems, upwelling-induced stable marine layers, and the generation of winter storms along western boundary currents (Figure 4). In each case, the ocean gives rise to weather patterns that affect everyday life. In each case, too, our understanding and predictive capability fall short of that desirable for both scientific and practical purposes.

4. Biogeochemical cycles

This is a particularly topical issue, due to concern over potential global warming and its mitigation. While carbon fluxes are currently being studied in the open ocean (e.g., by JGOFS, the Joint Global Ocean Flux Study), less attention has been directed at the coastal ocean, despite its substantial (30%: Mantoura *et al.*, 1991) contribution to global ocean primary productivity. While the coastal ocean is substantially different from the open ocean, the central questions are the same: how much carbon is utilized biologically, how much of it is derived from the atmosphere, and how much is deposited in sediments? Understanding the introduction and usage of nutrients in the coastal euphotic zone is closely related to understanding coastal primary production. Other chemical constituents must also be considered. Dimethyl sulfide (DMS), for example, is a sulfur compound generated in the ocean, but which readily escapes to the atmosphere where it plays a key role in cloud formation, hence global albedo.

5. The coastal sedimentary record

One of our major tools for studying the earth's past is the oceanic sedimentary record (Figure 5). Both long-term changes in "average" conditions, such as ice ages, and sudden extreme events, such as tsunamis, are recorded there. However, interpreting this record of the dynamic coastal environment is difficult. Developing a good understanding of the present coastal setting and how it controls sediment properties is key to gaining the ability to interpret the record.

6. Global climatic change and the coastal ocean

All of the above issues relate to potential climate change, but more are involved (e.g., Mantoura *et al.*, 1991). For example, significant global warming would result in rising sea levels, causing potentially major changes in the land-sea boundary in some

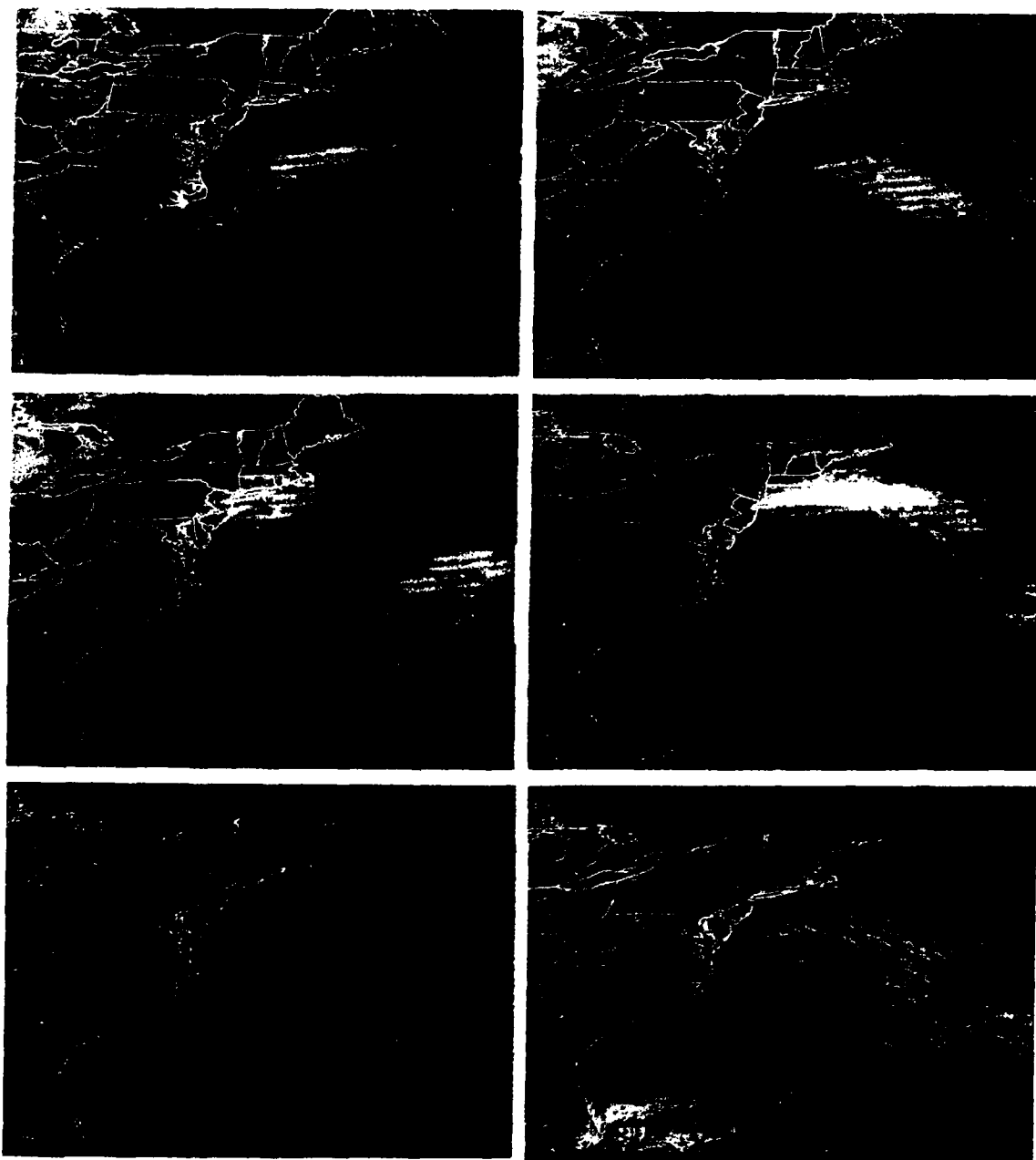


Figure 4: The photographs above are color-enhanced infrared and visible-light satellite images of the Presidents' Day Storm, 18-19 February 1979. Development of the brightly-colored cloud region over the Middle Atlantic and southern New England coasts corresponds to the rapid intensification of the surface cyclone and development of heavy snowfall across the Middle Atlantic states. Upper left — 0330 UTC 19 February 1979; upper right — 0830 UTC 19 Feb 79; middle left — 1300 UTC 19 Feb 79; middle right — 1830 UTC 19 Feb 79; lower left — 1330 UTC 19 Feb 79 (visible-light); lower right — 1830 UTC 19 Feb 79 (visible-light). (Photos courtesy of Chris Velden/CIMMS/University of Wisconsin-Madison).

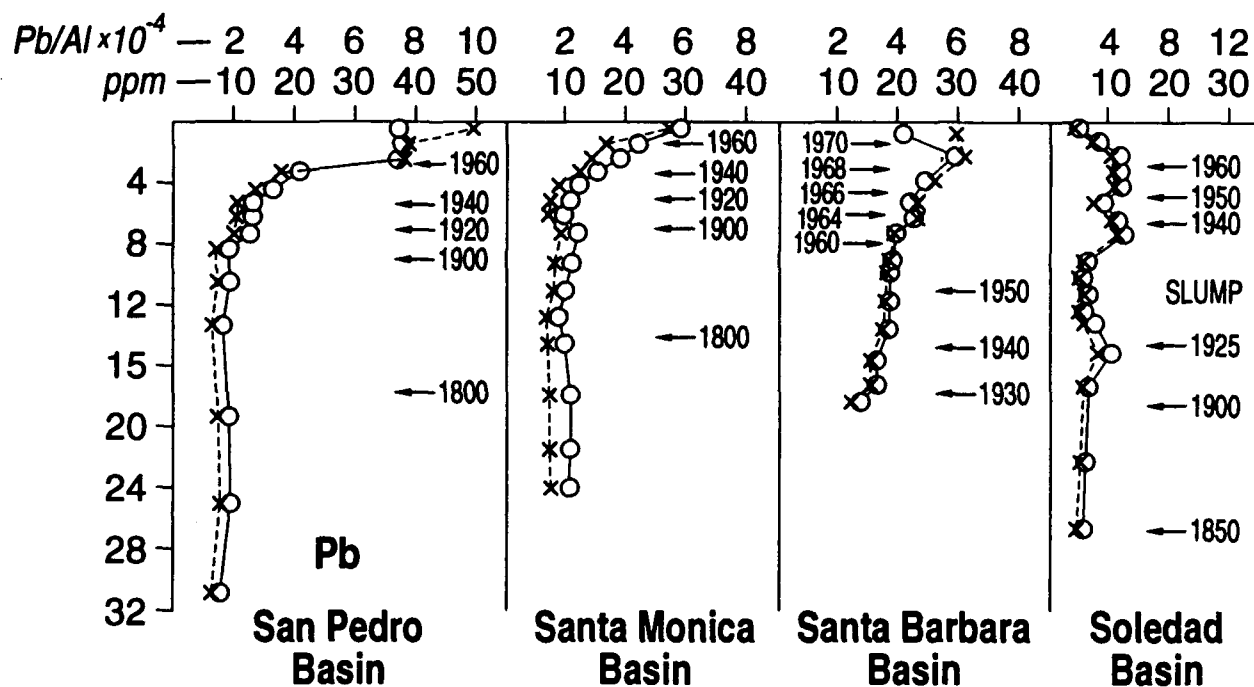


Figure 5: Profiles of Pb (dots connected by solid lines) and the Pb/Al ratio (crosses connected by dashed lines) in the seabed from four basins of the southern California continental margin (a. San Pedro, b. Santa Monica, c. Santa Barbara, d. Soledad). The chronologies were obtained by Pb-210 analyses. A dramatic increase can be observed in Pb content of sediment deposited during the latter half of this century. This increase is probably tied to automotive emissions. From Bruland *et al.*, 1974.

areas. Neither the coastal ocean's impact on climatic change nor the climatic change's influence on the coastal ocean can be predicted without assessing potential changes in coastal productivity, sedimentation, transport patterns and ecosystem structure.

Addressing these broad scientific issues requires a coordinated, large-scale (many investigator), interdisciplinary approach to the coastal ocean system. No single scientific discipline can address even one of the above issues, let alone the entire group. In response to this pressing need, coastal ocean scientists from a number of disciplines (biological oceanography, chemical oceanography, geological oceanography, marine meteorology and physical oceanography) have joined to form CoOP (Coastal Ocean Processes), an effort dedicated to addressing specific coastal issues that are beyond the scope of small teams of investigators. More detail is given below on the organization and specific objectives of CoOP, but the overall goal is:

to obtain a new level of quantitative understanding of the processes that dominate the transports, transformations and fates of biologically, chemically and geologically important matter on the continental margins.

B. Program Focus

Over the last two decades, tremendous progress has been made by physical oceanographers in understanding coastal tides and alongshore currents. For the many places where winds are important for driving shelf currents, simple quantitative models exist for predicting alongshore currents using large-scale alongshore wind data (Figure 6 and e.g., Brink, 1991). Because of the large spatial scale and energetic nature of these alongshore flows, they are readily observed, but they often obscure the generally weaker and less well understood cross-shelf flow component.

Because of the earth's rotation, steady flows tend to follow isobaths. This means that cross-margin transport requires special circumstances, such as the dominance of turbulence, strong time variability, or nonlinearity. With these constraints, cross-margin flow tends to be weak or to occur only sporadically in space and time, hence requiring fine-scale observations. Gradients in most biological, geological, and chemical quantities are, however, usually much stronger offshore than alongshore, making cross-margin transport crucial yet poorly understood. Intellectually, it is time to shift

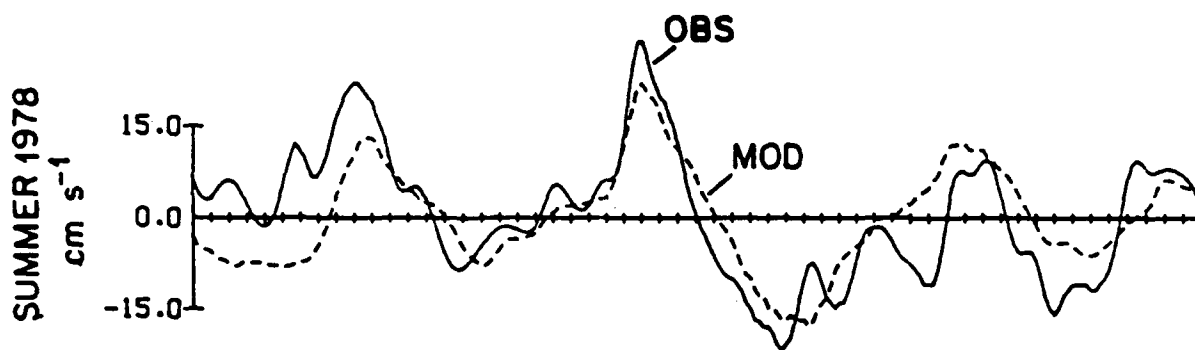


Figure 6: Observed (solid line) and modeled (dashed line) alongshore currents from over the continental shelf off Oregon, summer 1978. Positive velocity denotes northward flow. From Battisti and Hickey, 1984.

attention to these poorly understood flows and their implications for biological, chemical and geological processes.

The implications of cross-margin transport extend far beyond such purely physical issues as the exchange of heat and salt. For example, wind-driven cross-margin flow patterns often lead to coastal upwelling and the appearance of cold, high-nutrient surface waters near the coast. These cool waters stabilize the lower atmosphere, sharpen the atmospheric temperature inversion, and allow for unique meteorological phenomena, such as alongshore-propagating pressure systems. These systems, and the stability of the air, lead to considerable modifications in the air-sea fluxes of heat, momentum and gases. Because the atmosphere is often a primary driving agency in the coastal ocean, such atmospheric variations can feed back to the ocean. Thus, coastal currents and winds are closely coupled as part of a single system.

Sediments, which are delivered to the coastal ocean from rivers, glaciers, the atmosphere and beaches, are deposited as a result of physical, biological and chemical processes in the water column. It is well known that sediments do not always simply settle permanently where they are introduced: river-borne sediments, for example, are often found across the shelf and on the adjacent slope and ocean floor (Figure 7). Sediments can be initially deposited in an energetic nearshore location, but later transferred to more quiescent, often deeper, waters. Sea floor properties play a major role in determining the bottom stress, and hence the flow field above. The physical cross-margin exchange thus influences the geological properties, and the sediments in turn affect the flow properties in the overlying water column.

Biological processes in the coastal ocean are strongly determined by cross-shelf exchanges. Nutrients often enter coastal waters from onshore or offshore through, for example, estuarine outflows, coastal upwelling or intrusions associated with boundary currents (Figure 8). These new (as opposed to biologically recycled) nutrients help fuel primary production and the well-known high productivity of the coastal ocean. The resulting community structure, too, is influenced by properties of the flow field, for example the thickness of the surface turbulent layer or convergence at fronts. It is not sufficient to characterize biological processes in terms of primary productivity alone. Other parts of the ecosystem consume phytoplankton, recycle nutrients, and produce the fecal pellets that can lead to accelerated sinking of particles. In addition, benthic biota rework the sediments and modify the bottom characteristics. Thus,

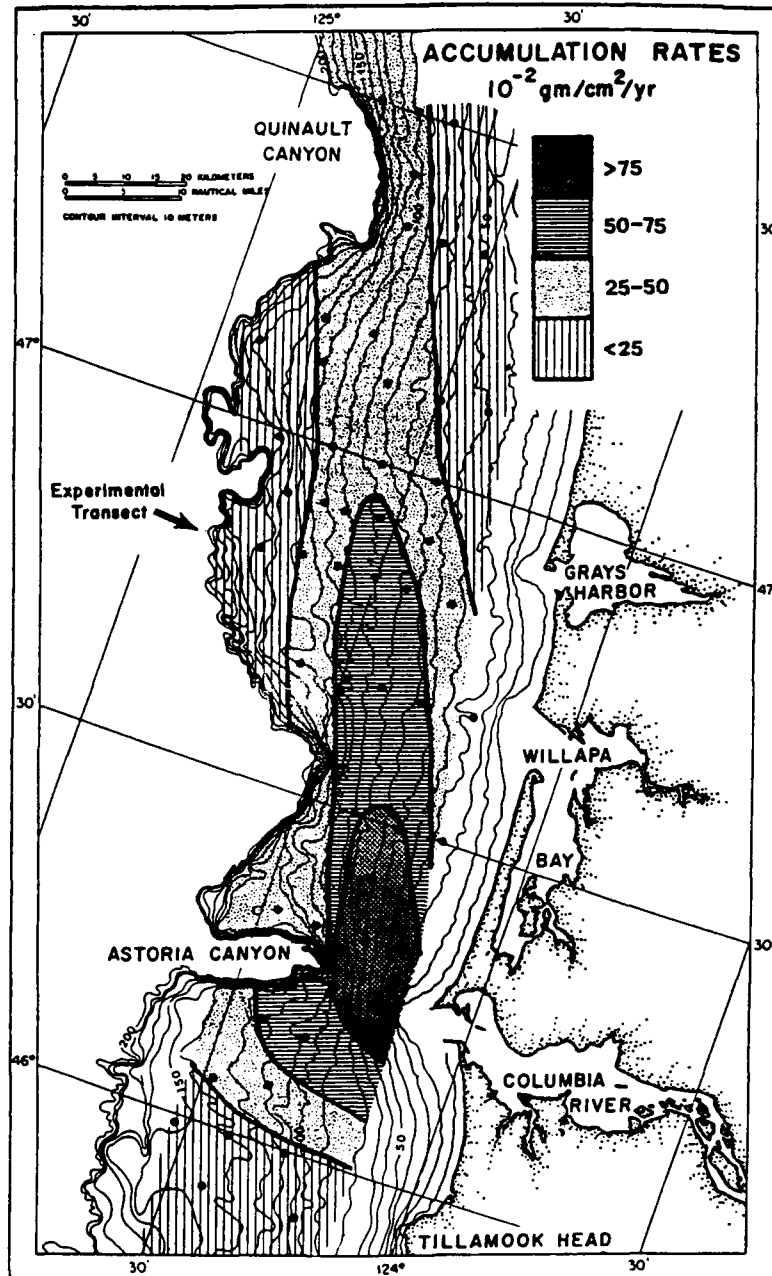


Figure 7: Sediment and associated chemical components released from the Columbia River are transported along and across the Washington continental margin. (a) The dispersal system can be traced by its path of high accumulation on the shelf which intersects Quinault submarine canyon (Nittrouer *et al.*, 1979).

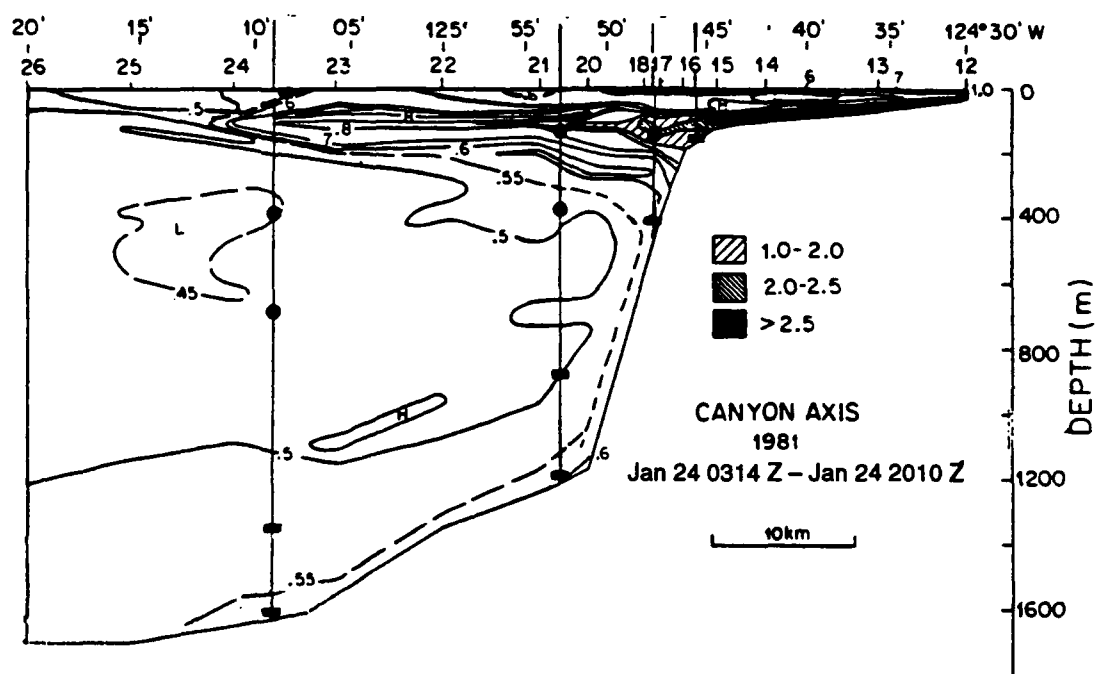


Figure 7: (b) Sediment escapes the shelf at Quinault canyon as a mid-water plume of turbid water, which loses sediment (through settling) to the floor of the canyon and deeper portions of the continental margin (Carson *et al.*, 1986). Isopachs of light attenuation contours (m^{-1}) are shown. Longitude and station numbers are given across top. Vertical lines represent mooring locations.

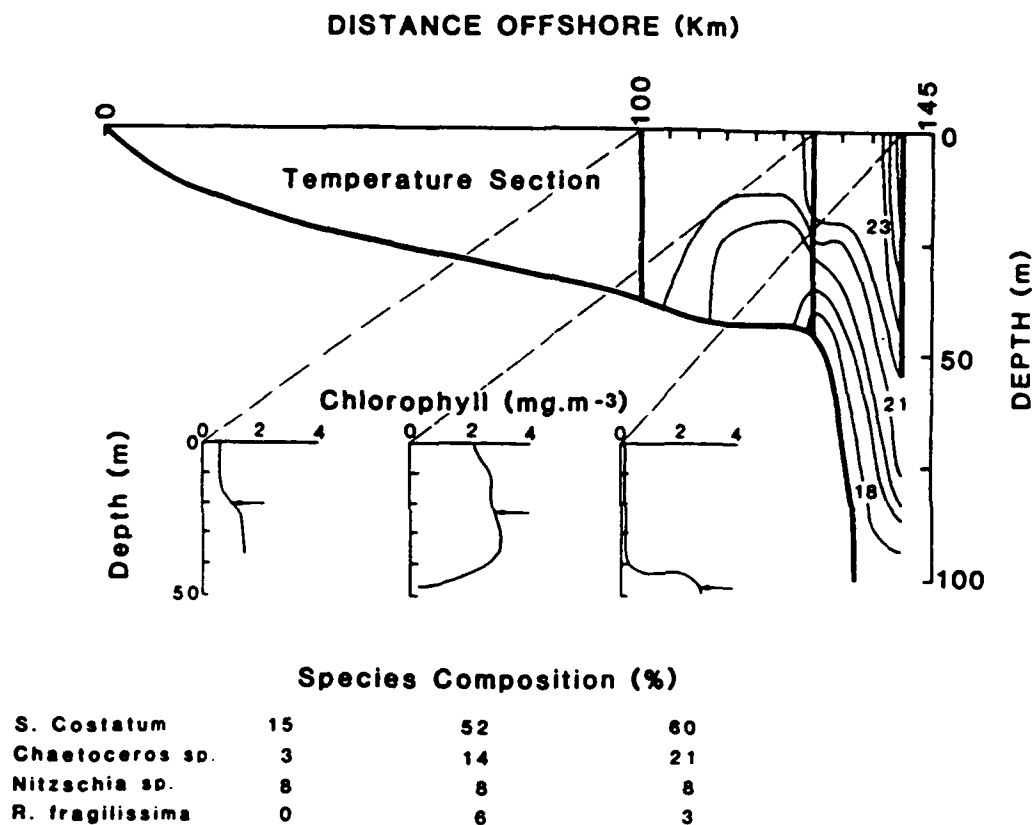


Figure 8: Aftermath of an upwelling event in outer shelf waters off the southeast U.S. From top to bottom: temperature section, vertical chlorophyll *a* distribution at three stations, and diatom species composition at depths indicated by the arrows. The species composition suggests that the subsurface chlorophyll maximum layer just seaward of the shelf break was formed by sinking and offshore advection of diatom-rich upwelled waters previously located over the outer shelf. From Yoder, 1985.

biological processes depend heavily on cross-margin exchange and themselves do much to influence chemical and geological properties. Once again, cross-margin exchange is at the center of an interactive system.

Chemical distributions in the coastal ocean are often characterized by cross-margin gradients associated with both inputs and *in situ* processes. Terrestrial runoff, for example, injects solutes which can react either directly with seawater, with biota or with particles to form new species to be removed to the sediments. Such reactions are thus mitigated by transport and by geological or biological processes. Different mixes of processes can affect materials entering from the bottom, surface or offshore boundaries. Understanding and predicting chemical processes thus requires study not only of solute distributions, but also of inputs, transformations, and removal, all in the context of the physical transport.

The common threads through the above discussion are the interdependence of all of the disciplines and the central role of cross-margin exchange. It is recognition of these connections that motivates and gives structure to CoOP.

C. What is CoOP?

CoOP is an interdisciplinary scientific program aimed at gaining quantitative understanding of important coastal ocean processes. The coastal ocean is too geographically diverse to allow a comprehensive, shelf-by-shelf approach. Rather, we attempt to isolate important processes having wide applicability and to study them intensively in locations where they dominate. Using improved observational understanding and allied improvements in models, results will be generalized to address issues on broader geographic scales. In addition to relatively short-term (1–2 years of field work) process studies and modeling, CoOP will encourage long time-series measurements at a few locations in order to probe interannual variability and the effects of rare but energetic events, which can dominate the variability and mean properties of many oceanic phenomena.

CoOP has the following important attributes.

- CoOP is interdisciplinary. We recognize that substantial advances clearly require more than single-discipline approaches, and that many of the problems of the different coastal ocean science disciplines are strongly coupled.

- CoOP is intended to undertake large-scale, many-investigator observational efforts. Smaller-scale efforts are much better left to individual investigators and to traditional funding sources.
- CoOP aims to reach quantitative understanding of scientific problems. We can now step beyond qualitative results to obtain the quantitative interpretations critical for model development and improvement. As part of our approach, we will seek to develop unifying, quantitative mathematical models of interdisciplinary oceanic phenomena.
- The scientific focus of CoOP is on cross-margin exchange. Because net exchanges depend critically on the vertical distributions of properties and particles, the structure of the entire water column must be resolved.
- CoOP efforts will be centered on the world's continental shelves (extending shoreward to the surf zone) and on the continental slope, extending on to the continental rise as necessary. This focus includes large inland water bodies having similar processes. Estuaries and offshore regions will be studied to the extent that they harbor natural extensions of shelf or slope processes.
- CoOP is distinguished from large programs such as JGOFS (Joint Global Ocean Flux Study) and GLOBEC (Global Ocean Ecosystem Dynamics) by its exclusive emphasis on the coastal ocean processes and by its focus not being limited only to biogeochemical cycles or to ecosystem dynamics. CoOP is intended to embrace interdisciplinary problems which encompass pressing issues in biological oceanography, chemical oceanography, geological oceanography, marine meteorology and physical oceanography.

The following sections provide a more thorough description of CoOP's objectives and proposed structure. We intend to lay the groundwork for a scientific program now, with the understanding that future broad community and agency involvement will bring about the definition of specific research.

II CoOP Science Objectives

The general CoOP goal provides a theme, but it is not specific enough to allow a clear vision of the sorts of interdisciplinary problems to be approached. Thus, five better defined objectives are described below. Each of these objectives encompasses a number of more specific problems to be studied. While not all of the individual problems posed span all disciplines, each must be solved to allow broader progress.

All of the objectives relate closely to the central issues of cross-margin transport and the accompanying biological, chemical and geological transformations. The second and third objectives relate specifically to the vertical structure of the water column. This is important because cross-margin transport processes tend to vary with depth, making vertical distributions critical in defining net transport. The second and fourth objectives deal with major sources of quantities that strongly affect processes in the coastal ocean. Finally, the fifth objective addresses primarily non-physical (albeit strongly physically mitigated) processes that are central to the transformations and fates of materials in the coastal ocean. The objectives described here allow overlap and are not unique subdivisions, but they are a rational sorting of the broad CoOP goal into scientifically manageable concepts.

II-A. To understand, quantitatively, the mechanisms, rates, and consequences of cross-margin transport of momentum, energy, solutes, particles, and organisms.

1. Background

a. Alongshore and cross-margin transport.

On continental shelves, flow parallel to isobaths is normally large in comparison to that across isobaths (Figure 9 and e.g., Allen *et al.*, 1983; Lentz and Winant, 1986). However, relatively large cross-margin changes in concentrations of dissolved and particulate materials, compared to along-shore variations, can allow large cross-margin material transports even with weak cross-margin flows. Also, cross-isobath transports link coastal and estuarine realms to the deep sea. Although substantial cross-margin transport of solutes, particulate matter and nutrients occurs, the mechanisms and sites of this transport are not well-known (e.g., Walsh *et al.*, 1988a; McCave, 1972). Cross-margin transports of plankton, solutes and particles are controlled in part by benthic boundary layer flows, coastal upwelling and downwelling, internal waves, the interaction of shelf waters with boundary currents and density currents (e.g., Hannan, 1984; Grant and Madsen, 1986; Shanks, 1988; Allen *et al.*, 1983; Brink, 1987). Some well-known results of cross-margin transport include the following.

- Long-term, large-scale changes in shoreline position in response to changing sea levels or energy regimes involve cross-margin sediment transport (e.g., Wright, 1987).
- Upwelling can cause shoreward transport of nutrients and larvae whereas near-bottom flows can entrain and transport benthic larvae and particles (e.g., Pineda, 1991; Wright *et al.*, 1991).
- The cross-shelf movements of planktonic larvae from one environment to another are fundamental to the life cycles of many organisms (e.g., Sulkin *et al.*, 1980; Banse, 1986; Farrell *et al.*, 1991).

Along relatively straight coasts, cross-margin variations of momentum, energy, solutes, particles, and organisms are usually much greater than alongshore variations. Hence, even weak cross-margin flows produce substantial transports that are important

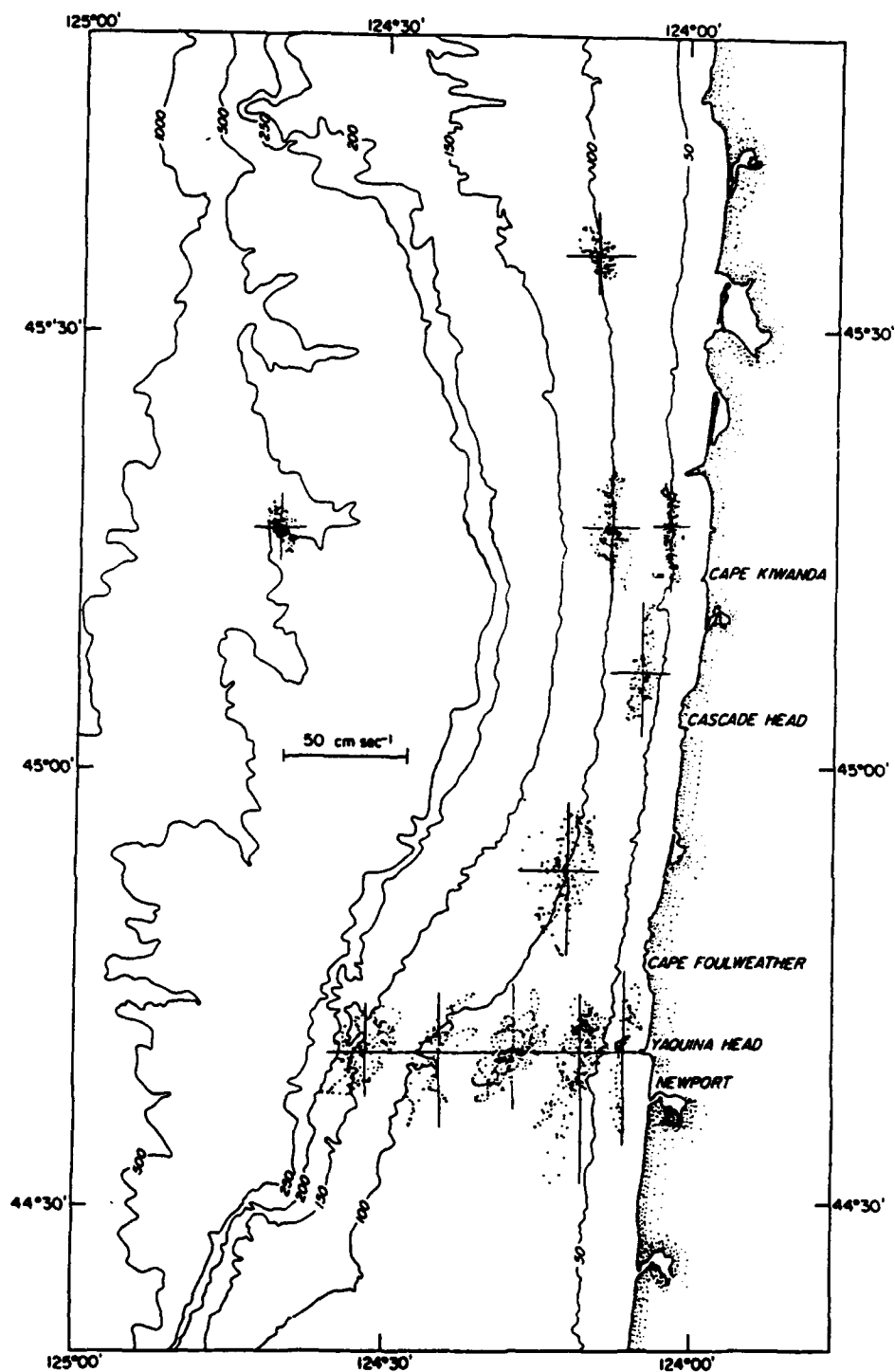


Figure 9: Scatter diagram of current fluctuations measured over the Oregon shelf. The distance of a dot from its origin is proportional to speed, and its angular location indicates direction. Tides and mean currents have been removed. From Kundu and Allen, 1976.

in determining the sources, sinks and temporary storage of materials. The relatively short scales of cross-margin variability also require that property distributions and transport processes be examined with greater spatial resolution than for alongshore distributions.

However, cross-margin flow and material transport cannot be understood without knowledge of alongshore processes. For example, alongshore transport can be important in bringing materials to sites of enhanced cross-margin flow, such as possibly off Cape Hatteras. Thus, quantification of cross-shelf transport requires a three-dimensional approach.

The inner and outer shelf differ in many important respects, some of which are noted in a previous CoOP report (Brink *et al.*, 1990). Often, different processes dominate currents at different offshore locations (e.g., Lee *et al.*, 1989). The mid-shelf regions of many continental margins are intermediate-to-long-term sinks for non-living particles, particularly muds, implying that convergences of particle transport occur in these regions (e.g., McCave, 1972; Nittrouer *et al.*, 1986). Furthermore, it is known that distributions of carbon in the seabed correlate with those of fine-grained sediments (Walsh *et al.*, 1988a). Because these sediments could represent a substantial sink of carbon, it is important to understand the processes by which shelves trap or export particles.

b. Vertical segregation of flows.

The direction of cross-margin flow often changes rapidly with depth, meaning that vertical variations of currents and properties (solutes, particles and biota) must be resolved in order to estimate net fluxes. For example, at mid-shelf, there is often a thin (of the order of magnitude of 10 m) turbulent surface layer, a non-turbulent interior, and a turbulent bottom boundary layer (e.g., Allen *et al.*, 1983). Each of these layers has its own distinct flow properties. As the coastal boundary is approached, net cross-margin flows averaged over space and time approach zero and the surface and bottom boundary layers overlap (e.g., Mitchum and Clarke, 1986). Net seaward or shoreward transports in this region of dissolved substances, particles, or larvae are likely facilitated by vertical segregation of flows. However, detailed measurements from this region are sparse. Limited nearshore field measurements of near-bottom flows during storms show substantial seaward velocities of 20 cm/s (Wright *et al.*, 1986; 1991), but we are not

yet sure what causes the flows. Because cross-shore flows are usually weaker than alongshore flows and because the vertical and horizontal scales of the flow are short, cross-shore transport processes are generally poorly characterized.

The extent to which passive (non-swimming) particles are mixed vertically and are transported by the flow at any particular level is often determined by boundary layer processes. The highest concentrations of particles are usually close to the bed (e.g., Smith, 1977), except in extremely productive areas or regions of turbid river inflow where near-surface concentrations are greater. Thus, boundary layer processes are closely tied to the problem of cross-margin transport. It is important to understand the vertical particle transport due to turbulence as well as the near-bottom velocity variations (e.g., Soulsby, 1983; Grant and Madsen, 1986). It is, of course, equally important that we understand the vertical swimming or buoyancy-altering behaviors of living particles, since they can be key factors in determining whether the organisms are transported shoreward or seaward. For example, upward or downward movements of larvae in the water column are known to be stimulated by light and pressure (Cronin and Forward, 1982; Mann and Wolf, 1983; Sulkin, 1984), but we lack substantial data on timing and rates of these movements over the shelf.

c. Cross-shelf carbon and nutrient transport.

Approximately 30% of the total organic carbon production of the oceans occurs over continental margins (Mantoura *et al.*, 1991). Some of this organic material is recycled or accumulates in sediments over the margins. However, the large margin-to-open ocean gradients in organic matter concentrations and production and the existence of cross-margin flows lead to the hypothesis that there is substantial offshore transport of organic materials. This export would require a corresponding import of the inorganic carbon and nutrients essential for photosynthesis from offshore waters, the land or the atmosphere.

Exchanges of materials at the air-sea and land-sea boundaries are discussed further in Sections II-B and II-D. Further, understanding of exchange across the margin-open ocean boundary is limited, but it is likely to be highly variable in time and space. Energetic offshore currents appear to play an important role in this exchange. For example, Eastern Boundary Currents (such as the California and Benguela Current Systems) have energetic variability that appears to help draw coastal waters offshore.

In the California Current System, this spatial variability is apparently due to instabilities modulated by coastal and bottom topography (e.g., Haidvogel *et al.*, 1991). The Gulf Stream, a Western Boundary Current, influences margin-open ocean exchange differently. Nutrients are supplied to the shelf waters via eddy-induced upwelling, cross-frontal exchange, and alongshore transport. There is also some evidence, from the occurrence of "plumes" containing high concentrations of particles, that the Gulf Stream is an avenue of export of organic matter to the open ocean (Fisher, 1972; Gawarkiewicz *et al.*, 1992).

2. Major Research Issues for CoOP

A set of interdisciplinary research goals, addressing how matter traverses the margin between the nearshore and the deep sea, follows:

- a. To determine the major physical processes forcing cross-margin transport and their variation across the margin, vertically in the water column and with time.
- b. To determine how turbulent processes affect flow near the surface and bottom, and how the associated stresses vary across the margin.
- c. To quantify nutrient, suspended particle, and dissolved organic material concentrations and understand the processes determining their structure.
- d. To determine how cross-margin transport affects planktonic life forms in the coastal ocean.
- e. To understand how sedimentation patterns are influenced by cross-margin transport.

II-B. To understand the atmospheric and air-sea interaction processes that affect biological productivity, chemical transformations and cross-margin solute and particle transport.

1. Background

a. Introduction.

Coastal physical processes are strongly affected by the land-sea boundary. For example, land-sea thermal contrasts contribute to the formation of the land-sea breeze, atmospheric coastal fronts, and wind-induced coastal ocean currents. The coast can create high spatial variability and substantially modify the wind field that drives upwelling, currents, and surface waves. As a consequence, processes involving air-sea exchange of heat, mass, momentum, and trace gases are highly variable over scales of tens to hundreds of kilometers. Stratiform (low-level) clouds, which affect the radiation balance significantly, can form over cool, upwelled water, and the convergence of marine air over the coastline can result in heavy precipitation and runoff. Pollutant dispersion, coastal erosion, coastal ecosystems, and numerous other characteristics and processes of the land-sea boundary region are thus affected.

Studies of coastal physical oceanography and meteorology are inherently interdisciplinary because of the atmosphere's dependence on oceanic heat and moisture fluxes and the ocean's dependence on wind driving. Traditionally, however, studies have rarely combined investigations of both environments to determine the extent of the coupling. This applies also to the gas exchanges between the atmosphere and the ocean, which depend on the structure of both the upper ocean and the atmospheric boundary layer. Interaction between the atmosphere and ocean biological or geological processes is usually more indirect; however, physical interaction between the atmosphere and the ocean modifies the cross-margin circulation and, therefore, plays an important role in most coastal ocean processes.

b. Local and remote wind forcing.

The importance of air-sea exchange processes to the flow and heat distribution in the coastal ocean is well-established. Wind-driven circulation over the continental shelf tends to be affected by both local and remote wind forcing. Local winds consist of two components; a nearly geostrophic part related to the atmospheric pressure

gradients and a part governed by the stress distribution near the air-sea boundary (the atmospheric Ekman layer). Measurements have shown that the response time of wind-driven currents on the continental shelf is sufficiently short that important changes can be effected by strong wind events, such as those caused by the passage of an atmospheric front or the interaction between larger scale weather systems and topography (e.g., Lackman and Overland, 1989). There is thus often a strong correspondence between the changes in the currents and the local wind forcing. However, a substantial fraction of the coastal ocean variability is in the form of large scale (of the order of magnitude of 1000 km) motions that result from remote wind forcing and can propagate many hundreds of kilometers alongshore (Denbo and Allen, 1987; Davis and Bogden, 1989).

One of the most important coastal phenomena is the wind-driven across-margin circulation that drives upwelling and downwelling. An equatorward, alongshore wind along an eastern ocean boundary produces an offshore ocean flow in the near-surface region (oceanic Ekman layer). This offshore flow is compensated by a deeper on-shore flow and a complementary upward motion that lead to the incorporation of cold, nutrient-rich deep water into the surface layer. These new surface waters act to enhance biological productivity and to stabilize the lower atmosphere.

c. Fronts.

The coastal ocean is characterized by a nonequilibrium sea state and by large variations in sea surface temperature. For example, upwelled water is often much colder than the ambient surface water so that sharp ocean fronts form between the nearshore, colder water and the warmer water offshore. These frontal regions represent areas of particularly intense air-sea interactions. Changes in heat transport from the ocean to the atmosphere produce sharp variations in the stability of the boundary layer, cloud cover, and presumably gas fluxes over distances of up to 100 km. The high biological productivity of the coastal environment makes it particularly important to understand this trace gas exchange in the presence of fronts.

Atmospheric forcing also affects the temperature and salinity fronts that develop between the shelf waters and western boundary currents. The observed water mass boundary can be partially maintained by fluxes across the air-sea interface and by properties of the boundary current. Surface cooling may intensify the frontal structure because the shallow shelf water is more affected by cooling than offshore waters that

are replaced by poleward advection. There is substantial feedback from this warm current to the atmosphere, allowing storms to develop (Figure 4), thus further driving the ocean (Section II-B.1.d.). Air-sea interactions also modify frontal boundaries that develop in buoyancy-driven and tidally-dominated coastal environments where air-sea heat exchange affects the strength of the front.

d. Storms.

Severe storms affect many coastal regions during the winter, and, to a lesser extent, the summer. Regional differences exist as illustrated by North America. Ocean storms affect the coast from California to Alaska, while extratropical cyclones move from the interior of the continent to the east coast. Particularly important effects are caused by cold-air outbreaks along the east coast and by rapidly intensifying storms over the Gulf Stream (e.g., Bane and Osgood, 1989). Tropical cyclones, including hurricanes, can affect the coast during summer and autumn.

Cross-margin transport off the east coast of the U.S. is substantially affected by a combination of wind and offshore, e.g., Gulf Stream, forcing (Lee *et al.*, 1989). The atmospheric effect appears to be most significant during cold-air outbreak episodes in winter, when the atmospheric forcing is strongly influenced by the large gradients in sea surface temperature.

e. Topography.

The interaction between the regional or mesoscale atmospheric pressure gradients and topography lead to complex wind fields over the coastal ocean. Locally intense winds occur in topographically restricted channels when larger scale disturbances produce an along-channel pressure gradient (Lackman and Overland, 1989). These "gap winds" produce a highly variable surface stress field through a local enhancement of the flow downstream of the topographic gap. Another example occurs where upwelling is particularly intense. The cold nearshore water cools the atmosphere, forming a shallow, stable marine layer capped by a large temperature inversion (highly stable layer) (Figure 10). During these conditions, the marine layer height is often less than that of the coastal terrain, leading to highly structured wind fields over the water in response to even small changes in shoreline orientation (Figure 11, Winant *et al.*, 1988), and to alongshore-propagating pressure systems.

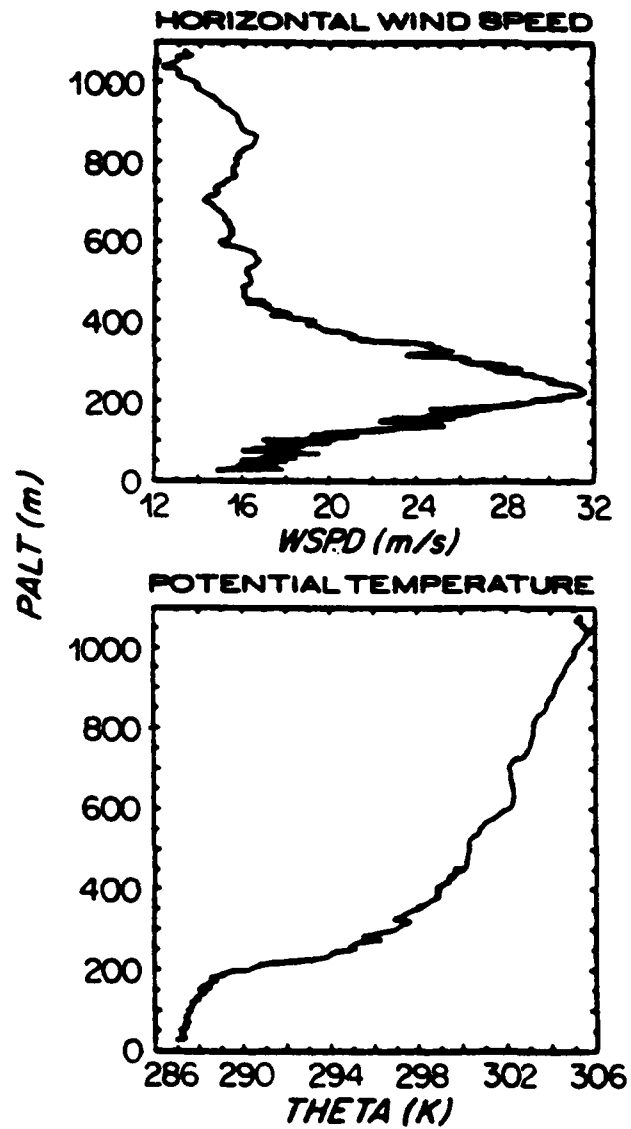


Figure 10: Vertical profiles of wind speed and potential temperature measured over an upwelling region off California. From Beardsley *et al.*, 1987.

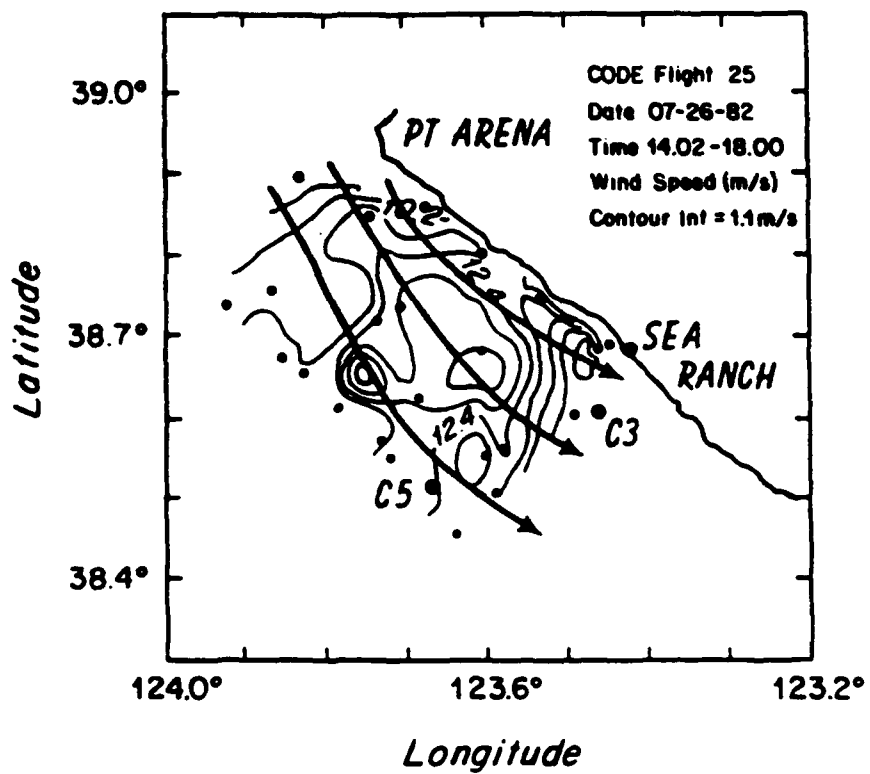


Figure 11: Contours of wind speed (light lines) and direction (heavy line) at 33 m height over an upwelling region off California. From Beardsley *et al.*, 1987.

f. Air-sea exchange processes.

The exchange of heat, mass, moisture, momentum, trace gases, and particles between the sea and the air is fundamental to an understanding of the ocean-atmosphere system. Although such processes are ubiquitous in the ocean, the coastal environment poses special difficulties because of variations in water depth, nonequilibrium sea state (due to limited fetch) and elevated biological activity. For example, atmospheric, chemical and biological issues might be intimately associated through feedback loops of aeolian inputs of biologically limiting elements and the production of biogenic greenhouse gases. It has been proposed that aeolian inputs of limiting nutrients borne with particles and rainfall limit primary productivity through lower light levels induced by coastal marine cloud formation condensed on byproducts of the reduced biogenic gases.

Momentum and heat fluxes are particularly important in determining the effect of the atmosphere on coastal circulation. Direct measurements are difficult, so empirical coefficients relating the turbulent flux to mean wind and thermal conditions (assuming an equilibrium sea state and horizontal homogeneity) are often used. This approach is suspect because of limited fetch and water depth and the heterogeneity of the coastal atmosphere. The estimation of trace gas exchange at the air-sea interface similarly remains uncertain in the ocean at large and is particularly complicated in the coastal environment for the same reasons as are heat and momentum fluxes. These fluxes are important if coastal marine productivity could control a proportionate amount of the global gas exchange of climate-controlling greenhouse gases. Present flux measurements and models developed for open ocean waters are not applicable to coastal water where the signs, much less the magnitudes, of gas fluxes are unknown.

Surface exchange processes depend greatly on the structure of the atmospheric boundary layer itself. The sea breeze, the interaction of a stable boundary layer with topography, boundary layer rolls, and clouds may all contribute to the variability of the surface fluxes (Elliot and O'Brien, 1977; Enriquez and Friehe, 1991; Rogers and Olsen, 1990; Koracin and Rogers, 1992). Horizontal variability of the surface temperature leads to the modification of the air and the development of atmospheric internal boundary layers (IBL). As air flows over an abrupt change in surface properties, an internal boundary layer develops within an existing boundary layer. For the case of cold air flowing onto a warm surface, an unstable IBL develops, rapidly replacing the existing boundary layer; for the case of warm air flowing onto a cold surface, a

stable IBL develops that may persist as a shallow layer until either the air is cooled by radiation or surface temperature increases to reverse the stability of the air. In either case, IBL processes complicate estimation of surface fluxes.

2. Major Research Issues for CoOP

Understanding the interaction between the atmosphere and ocean requires observing the three-dimensional structure of the atmospheric and oceanic boundary layers on the scales that provide the strongest feedbacks. A focus on small-scale interaction is important to elucidate the key processes controlling larger-scale coastal ocean and atmosphere fields. Small-scale (10 km, 1 hour), process-oriented studies should take place within a framework of longer-term, larger-scale measurements. This kind of detailed information is not presently available for coastal sites, yet it is required for a more complete understanding of the marine atmosphere, the coastal circulation, and its thermal structure. The following are major interdisciplinary CoOP goals related to air-sea interactions.

- a. To quantify the surface fluxes of heat, momentum and materials in the coastal environment.
- b. To determine the relative importance of small-scale and large-scale winds for cross-shelf exchange of water and materials.
- c. To determine the role of atmospheric forcing on coastal ocean fronts, and the atmosphere's response to these fronts.
- d. To determine the effects of storms, cold-air outbreaks, and other intense, short-lived atmospheric phenomena on air-sea exchange, coastal circulation and property distributions.
- e. To determine the effects of coastal topography on air-sea exchanges, coastal circulation and property distributions.

II-C. To understand the role of processes that couple the benthic and pelagic zones of the continental margin.

1. Background

a. Introduction.

Since the cross-margin flow component tends to vary considerably in the vertical, the vertical distribution of materials will be a strong determinant of its transport. Thus the processes that link different portions of the water column are critical. Vertical material transport couples the atmosphere, water column and sediments of the continental margin. For example, net downward transport of organic matter as large sinking particles, suspended colloids or dissolved organic matter (DOM) supports subeuphotic zone pelagic and benthic organisms. Downward transport of DOM and dissolved inorganic carbon by mixing or advection can result in carbon storage in subsurface water masses. Burial of particulate organic carbon in sediments is a long-term sink in the global carbon cycle: continental margin sediments are responsible for more than 90% of the total sedimentary carbon accumulation in the modern ocean (Berner, 1982). Downward transport of dissolved oxygen can be crucial to the survival of bottom-dwelling organisms in basins where the horizontal circulation is restricted. Downward transport is also responsible for the flux of atmosphere- and river-borne pollutants through the water column to the sediments.

Upward transport of materials is also important. Nutrients regenerated from particulate and dissolved organic matter in subsurface waters and sediments are returned to the euphotic zone, supporting "new" (as defined by Dugdale and Goering, 1967) production in surface waters. In shallow water, resuspension of sediments increases water column turbidity and can limit light availability to photosynthesizers. Sediment resuspension can also result in the remobilization of pollutants stored in sediments, as can biogeochemical processes in undisturbed sediments.

Even when little net transport of material occurs, vertical movements can be significant. An example is diel migration of zooplankton, where the advantage to the organism may be unrelated to material transfer, but may instead involve avoiding predation. Some net material transfer can occur nonetheless, as when the organisms feed at the surface and release fecal material deeper in the water column.

b. Advection and mixing.

Advection transports dissolved and suspended materials by the water's net motion. Strong vertical advection can be caused by the formation of dense water at the sea surface due to loss of heat to the atmosphere or to salinity increases due to brine rejection during sea ice formation or to evaporation. Brine rejection is particularly important over the extensive continental shelves bordering the Arctic Ocean and adjacent arctic and subarctic seas (Aagaard *et al.*, 1981; 1985). Wind-driven vertical advection results from convergence (hence downwelling) or divergence (hence upwelling) in the near-surface turbulent boundary layer. Eastern boundary regions are often sites of wind-driven coastal upwelling, which transports nutrients to the surface and so creates some of the most productive areas in the world's oceans.

Turbulent mixing can result from surface waves, internal waves, velocity shear near boundaries and other processes. The stability of the water column, often governed by surface heating, is an important control on the extent and intensity of turbulence, regardless of its source. The importance of turbulence lies in its ability to transport suspended or dissolved materials and to modify the habitat for living things. For example, Rothschild and Osborn (1988) suggest that turbulence can enhance feeding rates of zooplankton.

c. Particle sinking.

This mechanism is most effective for particles larger than 100 μm in diameter, such as zooplankton fecal matter and "marine snow" (particle aggregates) (Alldredge and Silver, 1988; Silver and Gowing, 1991). These larger particles often have densities only slightly greater than that of water, so that their sinking rate can be significantly influenced by vertical variations in water density. Much of the vertical transport of particulate material may result from purposeful movements of organisms, because of the material collected by sediment traps deployed just below the euphotic zone, much (11–80% in the northeastern Pacific) consists of living organisms (Silver and Gowing, 1991) even after the removal of large zooplankton ("swimmers"). Particles of all sizes undergo a variety of transformations, including aggregation with other particles, disaggregation, dissolution, adsorption and desorption of solutes, consumption by filter-feeding animals and decomposition by bacteria. Particle size, concentration and composition thus can change dramatically during transit to the bottom.

d. Bottom boundary layer transport.

Bottom stress and turbulence are largely associated with tides, currents and surface waves. The stress, in turn, constrains flow above the boundary layer. Interactions among currents, waves, small-scale bed morphology and sediment form cause substantial variations in bottom roughness and drag. For example, wave-current interaction causes bottom drag during storms 3 times greater on the middle and outer Middle Atlantic Bight shelf than that due to currents alone (Lyne *et al.*, 1990). In water shallower than about 200 m, wave-current interactions are much more intense than in deeper water, prevail for a much greater fraction of the time and are enhanced by ubiquitous, sharp-crested, wave-induced ripples at the sediment surface. Bottom stress is particularly important for geological processes, because sediments are not resuspended until a minimum shear stress is reached. Once resuspended, particles, including small organisms and larvae living in the surface sediments, can be transported for considerable distances, both vertically and horizontally.

Turbulent bottom boundary layers have their own unique flow environment, with the interaction of stresses and the earth's rotation causing a net transport perpendicular to the bottom stress. Convergence or divergence of boundary layer transport causes vertical velocities above the bottom that link the boundary layer to the interior. Another potential linkage may be particularly relevant to the coastal ocean. Specifically, if transport in the turbulent bottom boundary layer is directed offshore over a sloping bottom, eventually it may be advected beneath denser ambient water as it moves downwards. In this case, the boundary layer waters may separate from the bottom and move horizontally through water with the same density (e.g., Armi and Millard, 1976). Thus, water could leave the boundary layer by a nearly horizontal path. Also, sediment-seawater suspensions are denser than water alone, and these sometimes result in turbidity flows downward along sloping bottoms. These flows typically continue until enough sediment settles for the density difference to be lost; large flows can sometimes penetrate from the shelf to abyssal depths.

e. Benthic processes.

Particle alteration continues in the sediment-water boundary zone. In continental margin areas, particles may spend several hundred years in this active interfacial region before being incorporated in the permanent deposit. There are several key differences

between the bottom and the overlying water. Within the sediments and in a thin (of the order of magnitude of 1 mm) layer above, transport of dissolved solutes is by molecular, rather than turbulent, diffusion. High particulate organic matter concentrations in this porewater lead to high biomass per unit volume relative to the water column. Rates of oxygen consumption are thus high and oxygen resupply rates are slow because of molecular diffusion, so that oxygen depletion can occur even less than a centimeter below the sediment surface. Oxygen depletion in turn limits the penetration of benthic animals into the sediment and causes major changes in the microbial community and thus in sediment geochemistry. Anoxic sediment porewaters typically contain elevated concentrations of ammonium, phosphate, sulfide and trace metals, which can eventually reach overlying waters.

Organisms living in surficial sediments can accelerate rates of porewater exchange and sediment burial by their action on the sediments. Indeed, in areas with dense infaunal communities, biological processing may be the major means of transporting dissolved substances out of sediments and of burying freshly deposited particles. Bioturbation also can move buried particles back to the sediment surface and contact with the overlying water column. In addition, bioturbation has important effects on the stability of surface sediments and their susceptibility to resuspension.

Particles deposited to continental margin sediments commonly undergo many suspension-deposition cycles before permanent deposition occurs. Bioturbators can transport porewater or particles to the sediment surface from depths of at least 30 cm. Rare events, such as severe storms, turbidity flows and earthquakes and associated tsunamis, can disturb sediments to depths of several tens of cm. Molecular diffusion also allows exchange between the overlying water and sediment porewaters, even down to the depths where particles are no longer susceptible to upward transport. Ultimately, however, particles are buried deeply enough that interaction with the water column is not significant. This burial depth is roughly 1 m, corresponding to 10 to 10,000 years of sediment accumulation in the continental margin. Burial represents a major global long-term sink for carbon (about 0.15×10^{15} g C/year; Berner, 1982), as well as for other elements including nitrogen, phosphorus and sulfur (Bolin and Cook, 1983). During the shift from interglacial to glacial time, the main sites of organic matter deposition shift from estuaries and other nearshore locations to the continental slope, and the total carbon accumulation in margin sediments may increase as atmospheric

carbon dioxide levels decrease during glaciations (Muller *et al.*, 1983; Sarnthein *et al.*, 1987). This in turn suggests a feedback between sedimentary carbon accumulation and global climate change.

2. Major Research Issues for CoOP

The nature and intensity of processes coupling the benthic and pelagic zones of the continental margin vary horizontally (both alongshore and offshore), so research must address this horizontal structure. Research goals related to benthic–pelagic coupling are:

- a. To quantify effects of vertical mixing and advection on nutrient supply to the euphotic zone.
- b. To determine the vertical transports and distributions of carbon dioxide and oxygen in relation to the effects of air–sea exchange, cross-margin transport and biological processes.
- c. To quantify the export of dissolved carbon dioxide and organic matter downward from the euphotic zone via advection and mixing.
- d. To relate rates of particle sinking to biological production and consumption, cross-margin transports, physical properties of the water column and particle aggregation and disaggregation.
- e. To quantify the resuspension and horizontal transport of suspended sediment and its relationship to physical factors.
- f. To measure the rates of biological and chemical transformations in the sediments and their relationship with the exchange of water and material across the benthic interface.
- g. To investigate bioturbation and its effects on decomposition of organic matter, sediment–water exchange and stability of sediment to resuspension.
- h. To relate the rate of burial of sediment and its key constituents, such as organic carbon, to cross-margin transport processes, the quantity and composition of materials delivered to the sediment surface, respiration, irrigation, mixing by

sediment organisms, porewater-seawater exchange of dissolved substances and sediment resuspension.

II-D. To understand the nature and effects of terrestrial inputs on the transport and fate of solutes, particles and productivity in the coastal ocean.

1. Background

a. Importance of Terrestrial Inputs.

Ocean margins are the interface that controls the anthropogenic and terrestrial fluxes and fates of solutes, particles and productivity to and from the open ocean. Over 90% of the particles, trace metals and pollutants carried by rivers are sequestered in the coastal ocean (Mantoura *et al.*, 1991). The discharges of urban and industrial pollutants into the coastal ocean are increasing in many areas. Logging and agricultural practices also lead to enhanced discharges of solutes and particles. Conversely, freshwater discharges are often being reduced because of damming and water diversion for irrigation. Critical to understanding the consequences of these perturbations are studies that focus on the nature of terrestrial inputs and their effects on the transport and fate of solutes, particles and productivity in the coastal ocean.

b. Inputs from Rivers.

Terrestrial materials reach the coastal ocean by fluvial, glacial and aeolian means. Rivers carry both dissolved and suspended materials into the coastal ocean, and, in many cases, river-borne nutrients (Figure 12) stimulate primary productivity as suspended material settles and allows increased light penetration. Deltaic features are a consequence of particle deposition and they may be laterally displaced by shelf transport processes. In such cases the shoreline is characterized by extensive intertidal and lagoonal structures. Considerable terrestrial input of sediment appears to be associated with short rivers in rainy, mountainous regions (Syvitski and Milliman, 1992).

Approximately 0.5 billion tons of organic carbon are transported into the coastal ocean by rivers, roughly half of which is in particulate form (Degens *et al.*, 1990). Over 80% of modern organic carbon burial occurs in the coastal ocean, with slope deposition accounting for the majority of the burial (Romankevich, 1984). Much of this terrestrial organic material has characteristic isotopic and biochemical composition that can be used to trace the transport and fate of terrigenous material on the ocean margin.

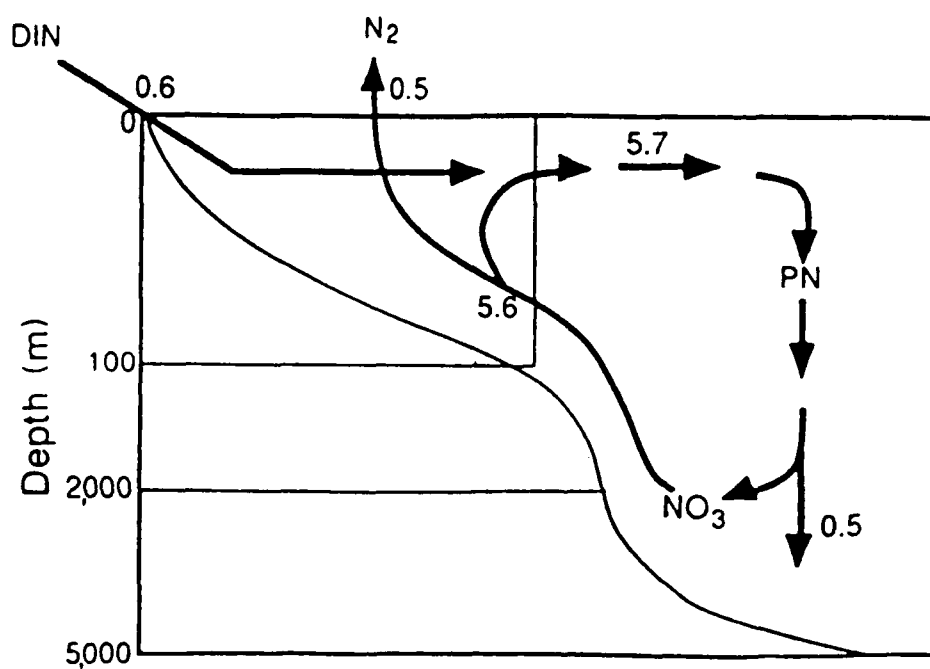


Figure 12: Estimates of global fluxes ($10^{14} \text{ g N yr}^{-1}$) of dissolved inorganic nitrogen from rivers (DIN), nitrate from deep water sources (NO_3), particulate nitrogen (PN) and gaseous nitrogen (N_2) in the continental margins. From Walsh, 1991.

The amount of solutes and particulate matter delivered to the coastal ocean by rivers depends on a variety of factors including the size of the watershed and the flow rate and morphology of the estuary, lagoon or embayment at the river mouth. For example, the Hudson River Estuary, with a low retention time, delivers high amounts of nitrate to the New York Bight. Conversely, a relatively long retention time in the Chesapeake Bay estuary results in efficient nitrogen retention with little export to the coastal ocean (Fisher *et al.*, 1988). Estuaries can process and remove much of the dissolved and most of the suspended particulate material and thus act as effective filters for terrestrial input to the coastal ocean.

Groundwater input also may be a means for dissolved substance input to the coastal ocean. On a worldwide basis, this has been estimated to be as much as about 10% of surface runoff (Zektzer *et al.*, 1973) although it is likely less, and for many dissolved materials it could be an important means of input to the coastal ocean. This would be especially true in coastal areas dominated by carbonate and karstic terrain where groundwater springs prevail. While the global volume of groundwater discharge may not be large compared to above-ground sources, it could have important contributions to some trace elements and tracers such as radon (Orr *et al.*, 1985), used to document horizontal fluxes.

c. Glacial Inputs.

For coastal areas in polar climates, melting ice can be the dominant source of particulate material and an important source of fresh water. Terrestrial sediments transported to the ocean by glacial ice can be released in several ways. Icebergs formed at calving lines release ice-rafted debris as they drift and melt (Anderson *et al.*, 1980). In the Antarctic, fine-grained sediments can be released from glacial ice below sea level, and can be transported in intermediate and bottom nepheloid layers (Domack and Williams, 1990). Many arctic areas receive turbid meltwater plumes, which spread into the ocean as surface features (Molnia, 1983). Stable stratification results from surficial freshwater layers formed by melting glacial and sea ice. This stratification increases the residence time of phytoplankton in euphotic zones, and can lead to high productivity (Smith and Nelson, 1985).

d. Atmospheric Inputs.

Aeolian transport and deposition is another primary input mechanism, particularly when the ocean is downwind of a source. In such cases natural and anthropogenic material from continental emissions can effectively supply the bulk of primary nutrients such as nitrogen and most trace metals. For example, in the South Atlantic Bight the input of trace metals via atmospheric deposition is greater than the input from rivers (Windom, 1981). Nitrogen inputs to coastal waters through precipitation can also be a significant fraction of total input (Duce, 1991). Acid-rain-stimulated phytoplankton production in laboratory experiments (Paerl, 1985) suggests that this input may contribute to eutrophication of coastal waters.

e. Buoyancy Flux.

Approximately $33 \times 10^3 \text{ km}^3$ of freshwater are delivered each year to coastal oceans by rivers (Milliman 1989). This runoff results in currents, stratification and fronts maintained by the density difference between freshwater and seawater. The freshness of the water thus acts as both a driving agent and as a tracer of the flow. The process is essentially nonlinear in character, hence not as well understood as wind-driven currents or tides. Depending on the size of the inflow, and on the strength of competing driving forces, buoyancy-driven currents may occur only within a few kilometers of the coast (as along the east coast of the United States), or can dominate flow on the scale of the entire shelf (as in the Gulf of Alaska, e.g., Royer, 1982). Sediment transport and deposition, biogeochemical fluxes, productivity, and ecosystem structure are all strongly influenced by buoyancy-driven circulation.

f. Coastal Productivity.

Coastal seas occupy 0.5% of the volume of the ocean but contribute roughly 30% of the primary production (Mantoura *et al.*, 1991). Nutrient inputs from rivers and the atmosphere contribute to this enhanced production. Several studies have demonstrated that annual differences in the production of phytoplankton, zooplankton and fish are positively correlated with yearly differences in river discharge. Many organisms depend on river outflows to disperse their young. The return of juveniles to the estuary is often dependent on density-driven circulation. Enhanced concentrations of plankton occur at convergence zones associated with buoyant plumes, thus facilitating the foraging and growth. However, in spite of the long-standing knowledge of the enhanced productivity

associated with terrestrial inputs to the coastal ocean, the cause and effect mechanisms that contribute to this enhanced production are not well resolved.

2. Major Research Issues for CoOP

Ocean margins represent the interface that controls the anthropogenic and terrestrial fluxes to and from the open ocean. Interdisciplinary studies that focus on the nature and effects of terrestrial inputs are critical to understanding these human-induced perturbations. The following important scientific goals will provide a better understanding of the effects of terrestrial inputs.

- a. To understand how buoyancy inputs affect stratification and the cross-margin transport of solutes, particles and organisms.
- b. To determine the effects of terrestrial (atmospheric, glacial, and riverine) inputs of materials, predominantly nutrients, on coastal productivity.
- c. To determine the variability in time and space of river-borne particle inputs and their effects on sediment deposition and transport.
- d. To establish the proportion of organic carbon input to the coastal ocean from terrestrial sources that is sequestered on the shelf and exported to the deep sea.
- e. To understand how coastal morphology influences the input of terrestrial material into the coastal ocean.

II-E. To understand transformations of solutes, particles and organisms across the continental margin.

1. Background

a. Introduction.

As water is transported across ocean margins, solutes, particles and organisms undergo significant transformations. For example, phytoplankton assimilate dissolved nutrient salts and convert them into organic molecules. Detritus and living phytoplankton sink through the water column to the ocean floor where they are grazed by benthic organisms or are buried. Copepods, larval fish and benthic larvae grow, metamorphose and die. These biological and chemical processes can often occur at relatively fast rates compared to rates of water exchange across ocean margins. Thus, quantifying rates of biological and chemical transformations is important to understanding cross-margin exchange processes. To make the next jump in our quantitative understanding of ocean margin processes will require interdisciplinary investigations focussing on rates of dominant biological and chemical transformations in relation to rates of transport. For purposes of discussion, transformations will be considered within two general categories: (1) biogeochemical processes and (2) population dynamics.

b. Biogeochemical processes.

An important and controversial question in oceanography is: What are the roles of ocean margins in global cycles of important elements such as carbon, oxygen and nitrogen? Margins occupy a small part of the total ocean surface area, yet they account for approximately 30 percent of ocean primary production (Mantoura *et al.*, 1991). Clarifying the mechanisms controlling the cycling rate of essential elements has taken on recent urgency because of the potential for human alteration of global geochemical rates. In many instances, biological processes mediate the cycling of elements and control the fates of many materials that enter the oceans. Our ability to make predictions and accurate models of biological controls on the fates and transformations of solutes and particles in the oceans is severely limited by our incomplete understanding of ecosystem responses to external physical and chemical processes, as well as of the internal structure and functioning of marine ecosystems. Understanding these mechanisms is especially critical for the coastal ocean because of its generally

high productivity (thus processing capacity), its substantial biological variability in space and time and its role as the conduit between the continents and the deep ocean basins.

The role of biological processes in mediating and controlling geochemical cycling of important elements is one of the major uncertainties in present models of global change. Virtually all agree that biological processes play a key role in the ocean carbon cycle and the cycles of related elements such as nitrogen and oxygen. However, the possible role of ocean biota as a sink for anthropogenic carbon dioxide is highly controversial, and no generally acceptable model has as yet been proposed explaining why biological transformations of carbon might be working significantly faster now than before the industrial revolution. This is a key issue that needs consideration during the next decade. Ocean margin food webs are prime candidates for consideration, since they may have been altered by eutrophication and other human activities (Walsh *et al.*, 1981; Smith and Mackenzie, 1991).

In the oceans, vertical fluxes of organic material, lateral fluxes between estuaries and shelf waters and between shelf waters and those of the deep ocean, and burial rates of organic matter in ocean sediments are not simple linear functions of primary production. These fluxes depend upon physical and chemical characteristics, such as rates and mechanisms of nutrient delivery, and upon various largely unappreciated aspects of the membership and structure of marine food webs in the euphotic zone, at depth and at the sea floor. The broad theme of how ocean margin food webs respond to external forcing and affect the fluxes of biogenic materials, their transformations and their fates are illustrated by the examples below.

(1) Primary Production: Determining the role of ocean margins in the cycles of major and minor elements requires that we know the rates of primary production and the sources of nutrients sustaining productivity. This primary productivity is controlled primarily by light and nutrients. Early studies of coastal phytoplankton stressed seasonal time scales and focussed on, for example, the dynamics of spring and fall blooms (e.g., Riley, 1947). Seasonal phytoplankton blooms in response to seasonal changes in water column stratification and incident irradiance are clearly important, but other physical, chemical and biological processes also affect the dynamics of primary production (Marra *et al.*, 1990; Walsh 1991; Yoder, 1991). In particular, recent studies show the importance of higher frequency variability in productivity in response to

temporal (e.g., wind events — Walsh *et al.*, 1988b) and spatial variability (e.g., frontal processes — Marra *et al.*, 1990).

Interdisciplinary programs emphasizing cross-shelf exchange are particularly well suited for studies of the processes affecting nutrient flux to ocean margin waters. Specifically, there are three potentially significant sources of new, inorganic nutrients to ocean margin euphotic zones: (a) rivers (see Section II-D.), (b) the deep ocean reservoir and (c) the atmosphere (see Section II-B.). For most margin systems, the ocean reservoir is the largest source of new, inorganic nutrients. Processes supplying nutrients from the ocean reservoir to ocean margin waters include: wind-driven effects, including upwelling (west coast of North and South America), eddy-induced upwelling and intrusion (southeastern U.S. coast) and bolus exchange (northeastern U.S. coast). For most margin systems, the dynamics associated with nutrient fluxes from the ocean reservoir are complicated and involve high frequency events (e.g., wind and eddy events), as well as seasonal changes in water density and currents. Biological oceanographers know the mean seasonal and annual rates of primary production for most ocean margins, at least at lowest order. However, there are two important time scales for primary production that are less well known and may be particularly well suited for CoOP investigations: (1) high frequency events (days to weeks) and (2) interannual events. Progress in these two areas will require studies on the scale envisaged by CoOP.

(2) Fate of primary production: In the absence of significant grazing, the fate of primary production is controlled by the sinking of phytoplankton. Sinking rates depend upon the taxonomic class of phytoplankton, cell size, shape and other factors. Where diatoms dominate (e.g., the spring bloom in the Middle Atlantic Bight), sinking is rapid and accounts for a very high carbon flux to the benthos (Falkowski *et al.*, 1988; Walsh *et al.*, 1988b). In contrast, vertical fluxes are quite low where the primary producers are dominated by cyanobacteria (e.g., subtropical shelves). For the latter, biogenic materials pass through long and efficient food chains that metabolize carbon and recycle nutrients (Michaels and Silver, 1988).

Various aspects of the grazer trophic level in marine food chains determine the flux of materials and explicitly the fate of primary production. The body size of the dominant grazers is one key variable affecting ultimate rates of transport, transformation and fate of materials created by primary production. Larger zooplankton create larger fecal pellets, which have greater fall velocities and thus induce much higher rates of

vertical export than occur in ecosystems where production is consumed by protozoans and small zooplankters (Michaels and Silver, 1988).

The processes that aggregate and disaggregate particles in the sea tremendously alter the transformation and vertical flux rates of materials in the coastal ocean. Aggregates of organic and inorganic materials, along with living and dead organisms, are referred to as marine snow. Marine snow has much greater sinking velocity than smaller individual particles. Consequently, the transport and transformation of materials are affected by all events (biological, physical, meteorological and chemical) that affect the formation or destruction of marine snow. Food web structure is a major influence on the generation and destruction of marine snow. However, further research is required for the precise understanding of which phytoplankton and other microbial taxa promote particle flocculation and of the effects that different grazers have in destroying and reprocessing marine snow.

New methods of detecting dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) imply not only a far greater pool of dissolved organics in the world's ocean than previously thought, but also that dissolved DOC fluxes and microbial utilization may be more important than earlier suspected (Sugimura and Suzuki, 1988). The coastal ocean is characterized by direct inputs and substantial fluxes of dissolved organics from the land and estuaries. Consequently, important questions emerge concerning the role of the bacterioplankton and other microbes in processing and transforming DOC and DON in the coastal ocean. A reasonable assumption is that different microbial communities process these materials with different efficiencies, depending on their physiological state and species composition. However, we know little about how changes in the microbial community affect the fluxes, transformations and fates of dissolved organic materials.

The nature of benthic communities affects the fate of biogenic materials that reach the sea floor. Because of the relatively shallow water depths in the coastal ocean, labile organic materials are more likely to reach the benthos there than in the deep sea. In some situations, where surface-to-bottom mixing occurs, benthic-pelagic coupling is especially significant. Similarly, when planktonic grazers are unable to keep up with phytoplankton blooms, the proportion of primary production that is processed and transformed by the benthos can be high. This can occur either because of life history constraints of the zooplankton, temporal variability of the phytoplankton or intense

predation on the grazer populations. It seems reasonable to expect that the actual utilization of biogenic materials by the benthos will vary with the structure of the benthic community, but we do not have a good understanding of just what changes in the benthos imply for the fate of these materials.

The extent and characteristics of bioturbation of the sea floor is also important to a complete understanding of biogeochemical cycling. Biological disturbance, by benthic organisms as well as by their consumers as they forage, greatly affects the burial rates of organic materials, pore water transformations of materials, and the microbial action within the benthos. These processes differ greatly as composition of the benthic community and of bottom-feeding consumers vary. Consequently, as in the previous examples, knowledge of ecosystem processes will be critical to developing enhanced understanding of biogeochemical fluxes and transformations, as well as fates of materials, in the coastal ocean.

c. Population dynamics.

Humanity has long been perplexed by erratic fluctuations in the abundance of commercially exploited marine populations, such as sardines, herring, squid, lobsters and crabs. Fluctuations in marine populations are not regular enough to be considered oscillations and their cause has remained mysterious. However, most biologists assume that marine population fluctuations are somehow caused by events in the offshore waters. To the extent that these events are related to physical, chemical, biological, and geological processes transporting materials across the shelf, questions of population dynamics are directly related to the goals of CoOP. An example will illustrate the point.

The great Danish marine biologist, Gunnar Thorson, observed that a majority of benthic and intertidal marine invertebrate species have a two-phase life cycle. The conspicuous adult phases of barnacles, starfish, snails, clams, worms and so forth are usually preceded by nearly invisible larval phases that live and feed in coastal waters for a few days to a few months. Most fish also have a two-phase life cycle. Thorson noted that two-phase species have large fluctuations in abundance when compared to otherwise similar one-phase species. Thus, the larval phase, and not the adult phase, is implicated as the point at which environmental conditions affect populations.

A particularly active area of ecological research has involved barnacle growth in the rocky intertidal zone in such diverse locations as Scotland, New South Wales and

the west coast of the United States. Classical ideas suggest that species success depends mainly on the ability for these animals to outgrow their competitors on a rock face (Menge and Sutherland, 1987). More recent results, however, suggest that success depends much more on the number of larvae delivered to a rock surface (Roughgarden *et al.*, 1988, 1991).

Thus the larval input rate (also called the "settlement rate" and the "recruitment rate") emerges as the major control on the ecology of rocky intertidal communities and, by extension, the communities of other coastal and deep-sea benthic habitats. Moreover, variation in the ecological processes that occur at different sites can itself be understood and predicted if the regional oceanographic context of the sites is known. Fortunately, the distribution of larvae in coastal waters provides clues for reconstructing the circulation pattern in those waters, so that the interaction between ecologists and physical oceanographers is potentially a reciprocally beneficial collaboration.

Population variations are likely to have effects on material transport in the coastal ocean. In general terms, abundances of particular organisms and consequently food web structure must affect the fate of carbon and nutrients in the coastal zone, but there have been relatively few attempts to address this question quantitatively, although Walsh *et al.* (1978) analyzed the effects of overfishing and the subsequent catastrophic decline in the Peruvian anchovy on sedimentary carbon accumulation.

2. Major Research Issues for CoOP

The following goals relate to the transformations of solutes, particles and organisms:

- a. To understand the important processes affecting rates of primary production, and the relation between primary production and the transport rates of dissolved nutrients to and across ocean margins.
- b. To determine the important processes controlling the abundance and activity of those taxa of animals and bacteria that directly, and indirectly through effects on rates of primary production, affect the fate of solutes and particles.
- c. To determine the important benthic and pelagic food web processes affecting rates of remineralization of organic matter.

- d. To establish the relative importance of biological, chemical and physical processes in the aggregation and disaggregation of particles.
- e. To understand how the composition of benthic communities affects rates of particle resuspension, diffusion of solutes and organic matter burial in sediments.
- f. To determine the conditions whereby benthic communities are controlled by local processes affecting adults (such as competition, predation and disturbance) or by large scale, water-column processes affecting larvae (such as upwelling or frontal dynamics).

III Cross-Cutting Issues in Coastal Ocean Research

A. Introduction

Several considerations are common to most of the CoOP objectives discussed above. For example, coastal ocean processes occur on a range of telescoping time and space scales. "Scale Integration" is thus a primary cross-cutting issue. Other unifying issues fall into two categories: temporal variability, including "Global Change" and "Infrequent, Significant Events," and spatial variability, including "Point and Line Sources," "Fronts," and "Topography."

B. Scale Integration

A full understanding of the coastal ocean requires knowledge about how processes on one scale integrate to affect processes on other scales. For example, the processes that control flow in both the atmosphere and the ocean are strongly scale dependent. These scales vary from seconds and fractions of meters for turbulent motions, to millennia and thousands of kilometers for global change.

Atmospheric motions occur on the synoptic scale (100 to 10,000 km) where winds are nearly in balance with the mass field, the mesoscale (10–300 km) where mass and motion fields mutually adjust, and the local scale (about 1 km) where turbulent effects are felt. Although large-scale patterns provide the coastal atmospheric setting, winds over the ocean react strongly to local influences. Thus, synoptic forcing acts to determine the mesoscale circulation. Mesoscale atmospheric motions cause variations of surface stress that, in turn, may control the structure of coastal ocean currents, in turn allowing feedback to the atmosphere. Further, stresses on smaller scales integrate to influence even the largest-scale winds.

Scale integration similarly affects other types of coastal ocean processes, a particularly clear example being the geological realm of strata formation. Sedimentary laminae on millimeter and centimeter scales are formed by physical processes occurring on time scales from hours to years. Many laminae, together, form sedimentary beds that are meters and tens of meters thick, representing centuries and millennia of sediment accumulation. A comprehensive interpretation of strata (recording the history of the coastal ocean) requires that all time and space scales and their interrelationships be examined. Similarly, biological processes on a broad scale can be taken

to be the summation over many individual interactions among individuals, groups of individuals, and species. These interactions occur within a highly variable chemical and physical setting, which causes the structure on a large scale to be determined by events on much smaller scales.

Understanding atmospheric and oceanic processes requires information over a large region of space for a long period of time. Usually, however, long-term, well-resolved measurements can only be obtained at a few points, e.g., by using moored instrumentation. Alternatively, ships, satellites or aircraft can provide good spatial coverage of numerous variables at the expense of temporal resolution. The heterogeneity of the coastal environment limits the usefulness of single-point, time-series measurements alone, especially in the vicinity of large spatial gradients or discontinuities (such as fronts) where the structure of the environment changes rapidly. Resolution of all important scales ultimately requires a combination of long time series obtained from several locations with detailed process-oriented studies allowing improved spatial resolution.

C. Global Change

Modern global change, resulting from either natural or anthropogenic causes, could result in climatic warming and sea-level rise. These two particular effects on the coastal environment are discussed below, but global change could also result in enhanced coastal storms, changes in precipitation patterns and runoff, increased cloud cover, salt intrusion into ground water, change in biological recruitment and species diversity and many other effects.

Although the effects of global change occur slowly, they are widespread. Among the first coastal areas predicted to be affected will probably be those at high latitudes, where primary productivity could be enhanced because of reduced ice cover and/or enhanced thermal stratification. Consequently the coastal ocean will play a greater relative role in carbon dioxide gas exchange, both as a sink and a source, thus influencing further climate change. The effects on nutrient cycling and carbon burial, which depend on food web structure, are very difficult to predict. Presently, shallow arctic and subarctic seas have benthos-dominated food webs and a relatively large fraction of the primary production reaches the benthos because of limited pelagic cycling. This situation could be altered by global warming.

Sea-level rise will cause migration of coastal environments and perhaps, in some areas, formation of new environments, such as coastal lagoons and intertidal areas. The proportions of these areas that remain aquatic or become terrestrial will be determined by the availability of sediments. Although fluvial input of dissolved and particulate material dominates many coastal settings today, sources are likely to become more marine in the future. This would result because rising sea level and human dredging/damming activities increasingly cut off riverine supplies. Both particulate and dissolved components in estuaries would thus include a larger fraction of material imported from the oceans. These effects and modifications are largely unknown, but interrelated.

D. Infrequent, Significant Events

Natural variability in the coastal ocean is punctuated by infrequent yet significant events. Such events may be divided roughly into three categories as follows: energetic, physical forcing events such as a severe storm (Figure 13); episodic inputs, such as the import of a red-tide organism into coastal waters; and significant anthropogenic events, such as a large oil spill. The nature and location of catastrophic events are often not predictable, but a sound understanding of extreme natural processes can allow for better response to sudden impacts.

Coastal ocean physical processes are driven by the atmosphere, the open ocean, and the land-sea fluxes. Strong, infrequent events may occur within each of these regimes. Energetic forcing is particularly important in the coastal environment partly because of the shallow water depths found there, which require that momentum, energy, and heat be absorbed by a relatively small volume of water. Examples of energetic forcing events include strong atmospheric storms, the impingement of an energetic open-ocean eddy (e.g., a Gulf Stream warm-core ring) on the edge of the continental shelf, and a period of extremely large river runoff. The occurrence of each of these can be relatively rare. For example, a given coastal region may be hit by a hurricane or typhoon perhaps only once every 25 years, and the storm itself may directly affect the coastal area for only several hours to days. However, the effects of the storm on bottom topography, vegetation and animal habitats may last for years.

Sediment transport is disproportionately large during high-stress periods (e.g., large storms). Because these particles usually come from the underlying seabed, the accompanying erosion can release interstitial fluid and dissolved components, and dis-

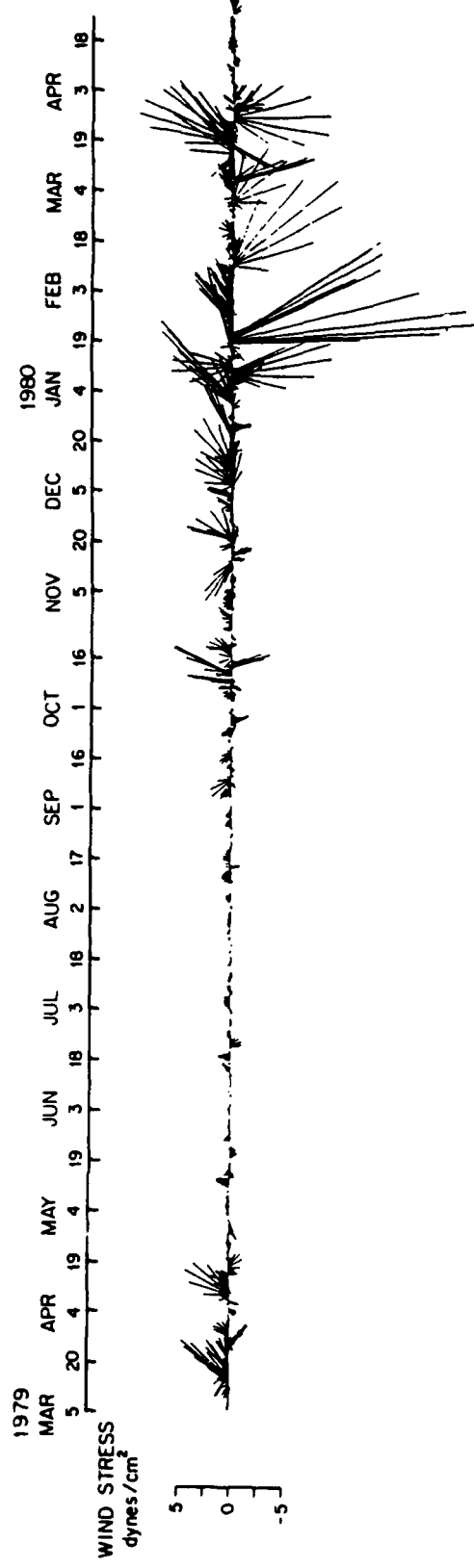


Figure 13: A year-long time series of wind stress south of Nantucket. The length of each line is proportional to the stress, and the wind blows in the direction of the individual line. Up is towards the east. From Beardsley *et al.*, 1985.

turb benthic communities. Subsequent redeposition creates thick stratigraphic layers that influence seabed biological and chemical characteristics for many years and are prominent features of the preserved geological record.

Episodic inputs of chemical and biological material can have dramatic, short-term effects on the coastal ocean. Toxic materials and organisms produce fish kills and enter other organisms that can retain the toxins for very long times. Injections of nutrients can cause blooms of phytoplankton. Often, the important materials in such events are transported into the coastal region by physical processes; these cases exemplify the close coupling between biogeochemical and physical processes in the coastal ocean.

Important measurement considerations exist for infrequent events. Long time series are needed to observe a single event, and several events should be observed in order to establish a reliable data base. In the analysis of these events, ordinary statistical methods may not be appropriate, and innovative approaches (such as perhaps fractal theory) will be needed.

E. Point and Line Sources

Inputs of fresh water, suspended sediments, hypersaline water, thermal discharges and a variety of anthropogenic materials often can be represented by isolated point sources or broadly distributed line sources (many overlapping small sources along a coastline). These two types of input can have quite different effects on the fate and cross-shelf transport of momentum, energy, solutes, particles and organisms. Line sources appear simpler, because they imply little or no along-shelf variability. Point sources, on the other hand, lead to both along-shelf and across-shelf variations.

Inputs of high-density or low-density water to continental shelves can also be sources of terrestrially derived material and drive the local flow. Low-density sources include rivers, estuaries and marshes. High-density sources include: brine rejection during freezing of seawater; cooling and evaporation by cold, dry winds off the land; and high suspended-sediment loads. Both high- and low-density inputs can behave as point or line sources. Examples of point sources include isolated rivers discharging fresh water. Large rivers (e.g., Mississippi, Amazon) also can be point sources of high suspended sediment concentrations. Examples of line freshwater sources include systems of barrier islands and tidal inlets along much of the U.S. east coast. Another line source is a cold-air outbreak, which produces high-density water over broad areas.

Sediment resuspension may be either a point or a line source: muddy deposits in the mid-shelf might act as line sources of wave-resuspended sediments, but dredge spoil sites and deltas may be better described as point sources of resuspended sediments.

F. Fronts

Although oceanic fronts can be found throughout the world's oceans, they are particularly abundant and intense in the coastal ocean. Freshwater-outflow fronts (Figure 14a) are found wherever waters running off the land (either point or line sources) make contact with saltier oceanic waters. In eastern-boundary-current regions, upwelling fronts (Figure 14b) occur as a consequence of wind-driven upwelling. In this case, the front separates nearshore cold, nutrient-rich waters from warmer, oligotrophic waters offshore. Tidal-mixing fronts (Figure 14c) occur at the boundary between tidally mixed and ambient, stratified waters. The location of these fronts depends upon the relative strength of the tidal currents and the tendency for the waters to restratify because of surface heating. Near the shelf break (Figures 14, 15), fronts can develop due to flow differences between the shallow continental shelf and the steep continental slope. In high latitudes, ice-edge fronts separate fresh water due to ice melting from ambient, saltier, oceanic waters.

Fronts are important for a number of reasons. By definition, they represent water property boundaries. Often, geochemical processes are intense where chemically distinct water masses meet. Cross-frontal shear might generate turbulence, significantly influencing vertical and lateral transports. Fronts are often the locus of high biological productivity. They cause substantial perturbations in the atmospheric boundary layer and help generate severe weather systems. Because fronts occur so frequently in the coastal ocean, any thorough coastal study must eventually come to grips with their presence.

Although causal mechanisms for different frontal types vary considerably, most fronts share a number of common features. For example, secondary (transverse) circulations can lead to downwelling or to upwelling. Also, cross-frontal exchange must often occur, but the mechanisms are presently poorly quantified, although instabilities and eddies seem to be possibilities.

Because fronts are concentrated, mobile, flexible features, any study of their behavior must be three-dimensional and must resolve their considerable time dependence.

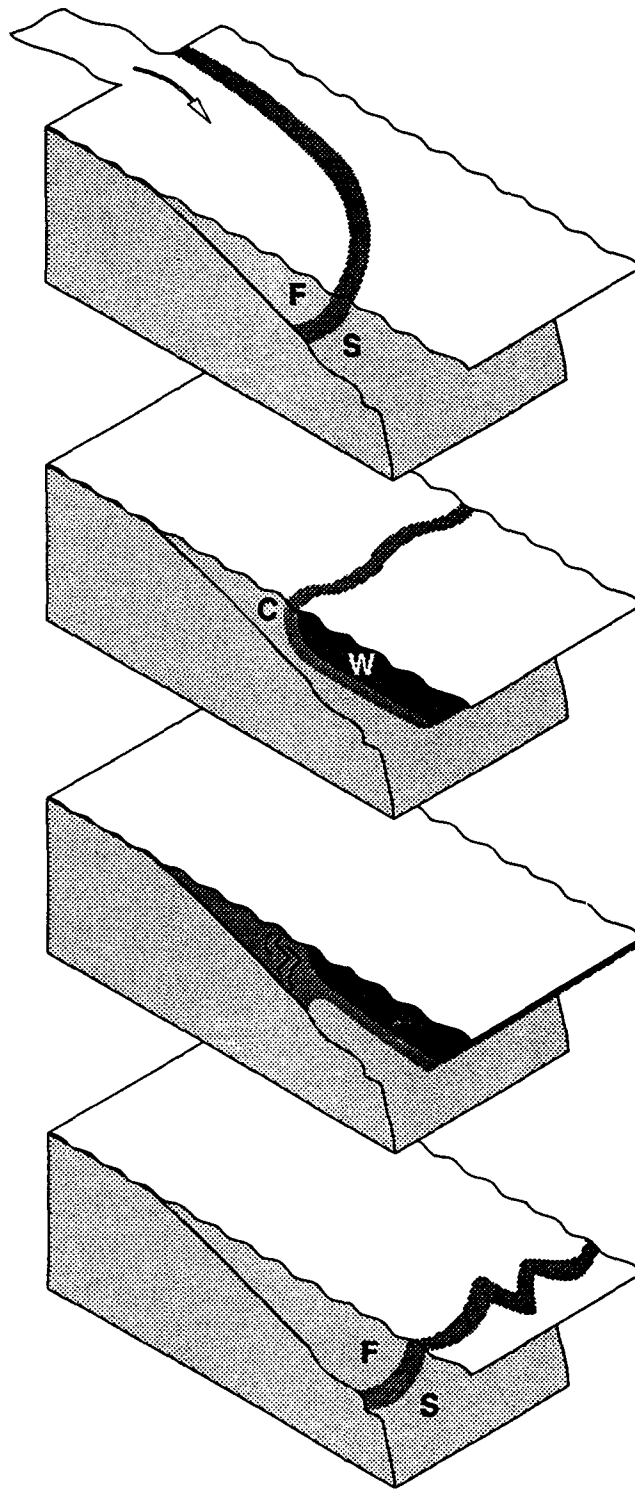


Figure 14: Sketches of different types of fronts. "F" indicates fresher water, "S" saltier, "W" warmer and "C" colder. Contours represent salinity or temperature, depending on the case. (a) Freshwater front. (b) Upwelling front. (c) Tidal mixing front. (d) Shelfbreak front.

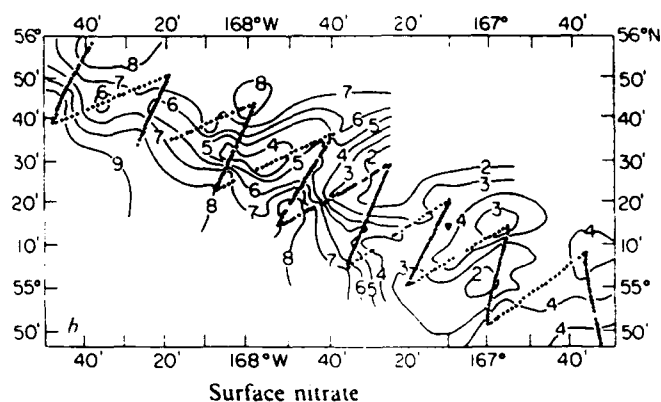
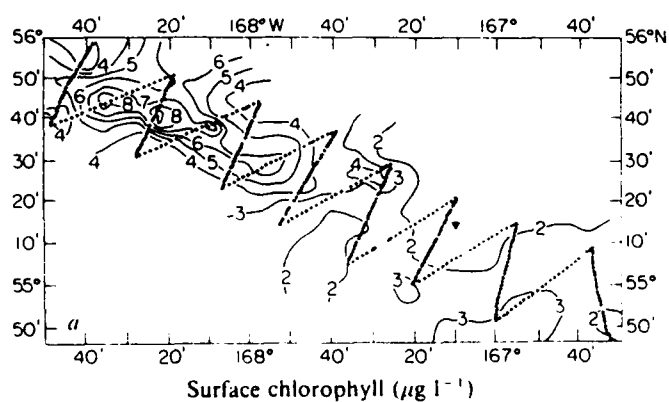
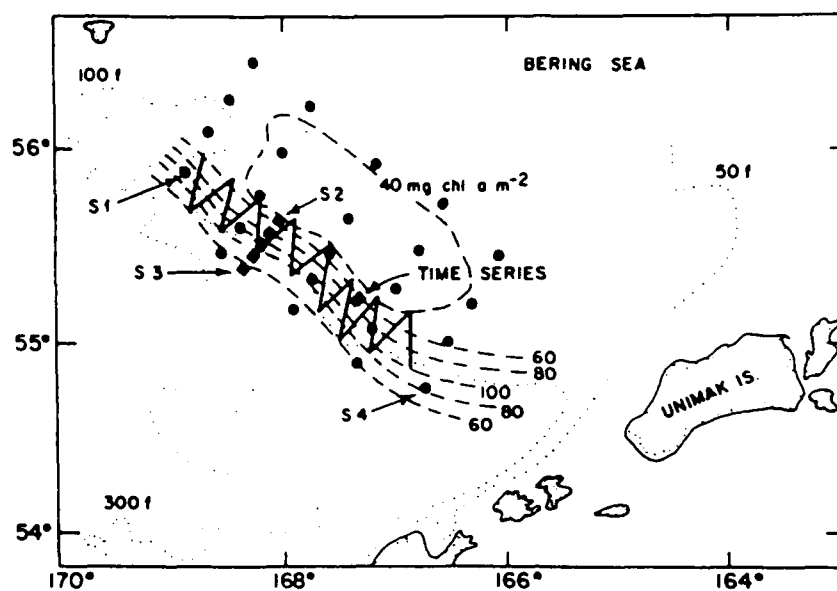


Figure 15: Effects of the shelf break front in the southeastern Bering Sea. (1) Upper Panel. Vertically-integrated chlorophyll *a* (mg m^{-2} ; heavy dashed line) in relation to bottom topography (fathoms, dotted line). Cruise track is solid line. (2) Surface chlorophyll *a* (mg m^{-3} ; lower left) and nitrate (mmoles m^{-3} ; lower right) along the same cruise track as shown in the upper panel. From Iverson *et al.*, 1979.

Sampling schemes should thus allow for high sampling rates and considerable flexibility. Because fronts generally occur in the upper ocean, meteorological effects are likely to be important. Chemical and biological features can be exploited as indicators of frontal circulation patterns.

G. Topography

Topographic variability characterizes the coastal ocean. The dramatic shelf-slope depth change influences most aspects of the flow field, including tides, wind-driven currents and mean flow patterns. In some cases, it presents such a barrier that distinct shelf water masses are formed and maintained. Even when such insulation of shelf from slope waters occurs, some exchange is still present. Very little quantitative understanding exists as to how and where this exchange takes place.

Other topographic irregularities of continental margins can also have considerable importance. Ideas about these topographic effects are often limited to untested physical models. In other cases, measurements exist that indicate the physical and biogeochemical importance of the effect. Achieving a truly quantitative evaluation of the overall importance of each effect is difficult, because isolation of single effects is nearly impossible. Therefore, in most cases CoOP studies will need to evaluate the role of compound topographic effects. Complex topography is the real situation in the coastal ocean and coupling between topographic effects could be important.

The presence of coastal mountain ranges can profoundly affect meteorological conditions and patterns of air-sea fluxes. For example, irregularities in the mountains lead to higher complexity, e.g., hydrodynamic jumps, shock and shadow zones, and locally dramatic wind reversals.

Tidal inlets and estuaries are gaps in the coastline connecting shelf waters with relatively calm water where sediments can accumulate and where unique biogeochemical processes can take place. Exchanges of water and material through these passageways can thus strongly affect shelf and slope processes. Major embayments in the coastline, such as the Gulf of Maine-Bay of Fundy system, allow tidal resonances, highly productive ecosystems, such as Georges Bank, and energetic flows that can control the distribution of sediments.

Submarine canyons, such as those of the Middle Atlantic Bight, appear to allow the constraints preventing shelf-slope exchanges to be broken. Canyons off the coast of Washington State are the locations of a predominant part of the shelf-ocean exchanges of chemical species, biota and sediments. Depressions or basins created by geological processes (tectonic or glacial) can act as efficient traps for sediments and organic debris as well as allowing isolation and distinct environmental conditions such as anoxia.

Many other topographic irregularities (e.g., straits, capes) are similarly important for determining air-sea fluxes, biological productivity, shelf-ocean exchange and the fate of sediments. The above examples are only a small sample of potential effects.

IV A Plan of Action

A. Governing Philosophy

The world's coastal oceans are geographically diverse. That is, each section of the coastal ocean has its own unique (or nearly unique) mix of attributes. Making thorough measurements and constructing models for each coastal region would be a herculean task, and is clearly beyond any reasonable resources available. The problem is simplified by our underlying belief that *there is a compact set of dominant processes that can be found in different mixtures in different locations*. Thus, the CoOP approach is to quantify key processes in a few areas well enough to model them effectively in a variety of regions. Gaining a more global understanding thus involves applying well-tested models to new settings.

Even with such a simple overlying scheme, a range of components is needed for CoOP. The primary foci are process studies and modeling. These efforts, in turn, must be supported by smaller, highly focussed, field efforts (exploratory studies, section IV-D.), as well as long time series measurements (section IV-E.), remote sensing (section IV-F.), technology development (section IV-G.), data archiving and quality control (section IV-H.), communications (section IV-I.), and facilities (section IV-J.). The steering committee will be responsible for the coordination of all these activities. Each of the varied program elements is discussed in turn below.

B. Process Studies

Each major, interdisciplinary field effort is to be focussed on a specific process, or set of processes. Such a criterion immediately implies that a specific geographical location (or small set of locations) be chosen where the desired natural processes dominate. For example, if the objective of a project were to understand productivity and particle transport in low-latitude settings dominated by carbonate organisms, the Belize shelf would be a better location than the Middle Atlantic Bight. Other choices of processes would naturally lead to other geographical selections. We recognize that there is no location in the ocean where only one process exists, so all important contributing processes must be allowed for in a process study. A number of possible studies were described at a CoOP meeting in July 1990 (Brink *et al.*, 1990).

Each CoOP process study would address interdisciplinary goals. An underlying tenet is that single-discipline problems, which generally require fewer resources and less complex organizational structures, should and would be done outside of CoOP. Each process study should address problems that can only be solved through an interdisciplinary approach. In certain cases, there may be problems specific to a smaller subset of disciplines, but that must be addressed before substantial broader interdisciplinary progress can be made. Also, there may be desirable locations where there is insufficient information to allow sensible scientific planning in some disciplinary areas. This situation would again require preliminary measurements to be made in order to proceed. Both types of preliminary efforts are addressed under "exploratory studies" (section IV-D).

Each process study, being focussed on a specific scientific goal, would be of finite duration, perhaps 2 years in the field and a total of 5-7 years including preparation, analysis and synthesis. Because a number of processes need attention, it seems likely that CoOP will entail a sequence of these major process studies, presumably ordered so that the fieldwork of any two major process studies will not significantly overlap.

Process studies will be initiated through interaction of the scientific community, funding agencies and the CoOP steering committee. Some criteria to be used are as follows.

1. The study must advance knowledge in one or more of the CoOP subject areas described in section II. That is, it must address specific interdisciplinary scientific objectives that fall within the CoOP umbrella. Further, the proposed study should relate to the broad CoOP theme of cross-margin transport of biological, chemical or geological materials. There could be situations where a CoOP process study would not include all CoOP subdisciplines.
2. The proposed process study must represent basic science rather than applied science. CoOP would welcome complementary efforts of a more applied nature, but the core study should lead to advances in scientific understanding. Further, CoOP will seek means to keep the applied science community informed on its findings.
3. Before recommendation of a project as a CoOP process study by the steering committee, a scientific implementation plan must exist. This plan should include

all scientific components, including modeling, needed to address the effort. No gaps (key components missing) in the plan should be allowed, nor should the plan include components extraneous to meeting the defined objective. The degree of complexity in the proposed scientific plan must be fully and rationally justified. We believe that it is better to tackle a small set of objectives well than a broader set poorly.

4. The proposed process study must be timely in that the objectives must be scientifically important and that the proposed study can be successfully completed using technology that will be available.
5. The CoOP steering committee will work with the broader community in defining the individual process studies. One model for doing this would be to have one or more scientists from the broader community (or from the steering committee) present preliminary ideas for a study to the steering committee. Should the committee see potential, the committee would find funds to sponsor an interdisciplinary workshop leading to a detailed implementation plan. Such a plan should detail and rationalize desirable geographical locations. The plan must also represent truly interdisciplinary (as opposed to multidisciplinary) research. The steering committee would then review the plan and make suggestions for improvement. Following this iteration, the steering committee would then either recommend, decline or postpone the plan. Following the recommendation, the committee would seek funding agency approval for the study, leading in turn to an open call for proposals from the funding agency. It is important to emphasize that the steering committee's role in the process is to help the scientists create a detailed and highly defensible plan for the process study. Substantial modification to this procedure may be required in dealing with funding agencies that select issues "in house," without initiation by academic scientists.
6. Modeling efforts must play a crucial role in each study. The modeling must be an integral part of the process study plan, and not a tangential activity. Modeling will be involved at all stages of the process study, from planning through analysis. It is expected that each process study will lead to substantial advances in modeling capability, so modelers must be involved in designing and executing the process study.

It would likely take about 2-3 years from the time of initial presentation to the steering committee until a funding agency announces an opportunity for proposals.

C. Modeling

Modeling represents a mathematical, quantitative expression of our understanding. As such, improved models would represent the culmination of a CoOP study. Further, prognostic models represent a means of expanding CoOP results to broader applications. For example, a proven capability to model the currents over a variety of shelves where process studies have occurred could presumably be extended for use in other, less-intensively studied regions. Experience will lead to a clear definition of the input variables needed for prognostic capability. Further, we require models to have interdisciplinary applicability, and not be simply, for example, physical or meteorological. In designing such a model system, scientists of all disciplines must recognize the complex, highly time-dependent nature of all natural systems over the continental margin. Further, we emphasize the need for many sorts of models, ranging from simple, analytically expressed exploratory models through degrees of complication to synthetic, highly realistic efforts requiring state-of-the-art computing systems.

The CoOP modeling effort is seen as being tightly coupled with the sea-going process studies described above. The modeling community should not be relegated to a life nearly independent of empiricism. Thus, there is no perceived need for a separate modeling program within CoOP, other than to address entirely technical issues. We envision an overall CoOP effort dominated by neither observational nor modeling aspects, although the blend is likely to vary from study to study.

D. Exploratory Studies

Not all CoOP field efforts will need to be the large-scale process studies discussed in IV-B. Rather, smaller-scale efforts may sometimes be required in order to meet overall CoOP goals. One type of well-defined exploratory study might be required in order to refine hypotheses and sampling plans in important regions (representing important processes) where little information exists in one or more disciplines. For example, information on plankton distributions and production in the Gulf of Alaska may be necessary for an interdisciplinary study of positive-buoyancy input systems. Another type of exploratory study would involve only a subset of disciplines, but would lead

to results needed for reaching broader CoOP goals, e.g., a study to refine estimates of air-sea gas fluxes.

Exploratory studies should be handled through the steering committee in a way analogous to the process study. An added criterion, though, is that the small-scale study be tightly linked to projected CoOP efforts. Smaller-scale, stand-alone coastal science should be carried out independently of CoOP.

The CoOP pilot study will soon be underway. The objectives of this effort are twofold. First, there was a desire on the part of NSF (National Science Foundation) to demonstrate that good, thoroughly interdisciplinary proposals could be generated by the community, thus demonstrating interest in a CoOP effort. Second, the effort must demonstrate that sound, quantitative interdisciplinary results can be obtained. The CoOP steering committee sponsored a workshop in La Jolla, California, in July 1990 to gather ideas about potential interdisciplinary efforts. This workshop led to a report (Brink *et al.*, 1990) summarizing the results and to a recommendation to NSF for studies. NSF, in turn, made public the opportunity for funding in these research areas. The proposals were reviewed by an interdisciplinary set of experts and a funding recommendation was made in late 1991. Thus, CoOP scientific research is to begin in mid-1992.

E. Long Time-Series Measurements

A comprehensive study of continental margin ocean science would necessarily include long time-series measurements in a few regions of such variables as wind, currents, waves, temperature, suspended and bottom sediments, nutrient content, key chemical species and plankton concentrations. Other variables may also be desirable, especially as new technologies become available. Such measurements would resolve low frequency variations (such as El Niño) and rare but significant events (such as hurricanes) and their effects on coastal systems. In nonlinear processes, such as sediment transport, such infrequent events can completely dominate the variability. Further, many important processes, for example ecosystem changes, are not stationary on the time scales resolved to date, meaning that existing measurements may not adequately resolve natural variability. A sufficiently long measurement program should resolve these difficulties, while defining the truly important time scales of the system. Long time-series measurements could also provide design information and retrospective context for the

process studies. On a more practical side, time-series measurements could prove to be a valuable tool for assessing anthropogenic effects on the coastal ocean system. Some thought has already been given to long time-series measurements, for example in the context of a Global Ocean Observing System (Baker *et al.*, 1990).

The logistical problems of maintaining a high-quality interdisciplinary measurement program over a period of a decade or more are considerable. For this reason, it is not clear exactly how the long time-series program should be executed. It may be far more sensible for an agency such as NOAA, with the capability for long-term commitments, to take on such a measurement program than to rely on grants to traditional research institutions. This would build on NOAA's existing experience with long-term measurements, such as with meteorological buoys. Further, considerable attention needs to be given to specifying measurement locations and variables that will be of lasting scientific interest. A mechanism similar to that used for defining process studies could be employed for designing long time-series measurements.

F. Remote Sensing

Most interdisciplinary studies of ocean margin waters in the 1990s will rely heavily on satellite remote sensing to locate features of interest during field programs and to help quantify temporal and spatial variability. The two sensors most generally useful to ocean margin studies are the thermal infrared and color scanners. These determine sea surface temperature (SST), and water clarity and phytoplankton pigment concentration, respectively, with spatial resolution of 1×1 km across a swath approximately 1500 km wide. NOAA's series of Advanced Very High Resolution Radiometers (AVHRRs) for SST will continue throughout the 1990s, and both the U.S. and Japanese space agencies plan color scanners beginning with the launch of SeaWiFS (Sea Wide Field Sensor) in 1993 (Table 4).

Regional antenna facilities similar to the Scripps Satellite Oceanography Facility (SSOF) are in place or are planned for the early 1990s, so that investigators hope to have a source of near real-time SST and ocean color data for modest cost. The technology is also in place to transmit satellite imagery to oceanographic ships. AVHRR and ocean color image analysis software is available for the small computers commonly available on most UNOLS (University-National Oceanographic Laboratory System) ships. Thus, sophisticated analyses of satellite imagery can now be done easily at sea.

Table 4 also shows that researchers in the 1990s will have access to data from satellite scatterometers, altimeters and synthetic aperture radars (SAR). Scatterometers and altimeters are most useful for large-scale circulation studies, because of their relatively coarse spatial resolution (ca. 25–50 km). Thus, their applications to continental margin studies will probably be limited to studies of boundary currents and perhaps outer shelf waters. SAR imagery is presently available from ESA's ERS-1 satellite and another source (NASDA's JERS-1) will become available beginning in 1992 (Table 4). SAR has very high spatial resolution (ca. 20 m) and is particularly useful for studies of sea ice.

G. Technology Innovation

For estimating fluxes of materials it is crucial to measure all variables of interest on comparable space and time scales. For example, monthly measurements of phytoplankton concentrations are difficult to combine with hourly measurements of currents to elucidate cause–effect relationships. In the past, such discrepancies in measurement techniques have led to considerable difficulty in analyzing interdisciplinary data sets. It is thus a major goal of CoOP, in coordination with other efforts such as GLOBEC (Global Ocean Ecosystem Dynamics), to encourage technological development to enhance measurement capabilities. Further, highly automated measurement systems will tend to reduce personnel and ship demands, at least on a per unit measurement basis.

We see technology development as being an ongoing effort throughout the CoOP era. It is particularly desirable to allow for instrument development well before it is to be used in process or exploratory studies. This will allow the developers to understand what capabilities are most needed, and will allow the observationalists to understand what capabilities are possible. Further, long lead time in development allows deployed systems to be well-tested in advance. In the early stages of CoOP, it would be useful to seek specific technology developments that would be useful for the duration of the program. Further, it could be given the same lead time for a process study that modeling will have.

H. Data Archiving and Quality Assurance

With any large, coordinated effort, data quality, access and archiving are all critical. Other efforts such as JGOFS (Joint Global Ocean Flux Studies), GLOBEC and WOCE (World Ocean Circulation Experiment) have dedicated considerable attention

to these issues, and we will benefit from their experience and duplicate their standards (where applicable). A general policy on data sharing and standards will be established. It seems likely that a standing committee will be required to establish and monitor data quality for CoOP. Likewise, some form of central data facility should be established. Whether this is simply a central "catalog" (describing who has exactly what information) or an actual data bank is yet to be seen. Some allowance must also be made for the maintenance of, and access to, preserved samples. Further, a data-sharing protocol needs to be established that allows ready access to information but still honors the rights of the initial observer.

I. Communications

Because CoOP will not operate in a vacuum, communications are important. This operates on many stages. First, a program office will need to coordinate activities and keep the scientific and management communities informed through the publication of a newsletter. Workshops will be needed to plan process and exploratory studies, as well as to address other specific issues. Further, coordination will be needed with other large-scale efforts such as GLOBEC, JGOFS and WOCE, as well as with related programs not sponsored primarily by NSF. Finally, it may often be desirable to coordinate with coastal ocean scientists from other nations. This can be done by encouraging individual cooperations as appropriate and circulating our newsletter to an international audience. To this end, we plan to exploit a proposed SCOR (Scientific Committee for Ocean Research) working group on coastal oceanography as a means of establishing program-to-program coordination.

It will be necessary to present CoOP results at coordinated, large-scale meetings accessible to the international coastal ocean science community and to applied scientists. This could be done most expediently by arranging special sessions at existing regular meetings such as the Ocean Science Meeting (AGU/ASLO) or through The Oceanography Society. This aspect of communications is especially important because CoOP results must be communicated to the user community in order to be of practical value.

J. Facilities

A major effort such as CoOP will call for a considerable commitment of instrumentation and research platforms. It may be necessary to create common-use dedicated

instrument facilities and gain greater access to existing coastal research laboratories. Specialized research platforms, such as ice-hardened ships and ROVs (Remotely Operated Vehicles), will likely be needed. Perhaps about 6 ship months per year will be required, as well as 300 hours of research aircraft time. Specifications for aircraft and ships have yet to be defined, and will often depend on the particular study. At present, UNOLS is studying coastal ship design requirements, and their findings will be highly relevant in this process. Innovative platforms, such as airships, may also prove highly desirable for CoOP.

**TABLE 4. Status of Major, Pre-EOS Ocean Spacecraft and Instruments
(as of fall 1991).**

Satellite	Sponsor	Instruments	Launch Date
DMSP Series	USAF NASA*	MR	June 1987
Polar Series	NOAA NASA*	IR	On going.
ESA ERS-1	ESA NASA*	ALT, SCAT, SAR, IR	July 1991
NASDA ERS-1	NASDA NASA*	SAR	February 1992
TOPEX	NASA CNES	ALT	July 1992
SeaWiFS	OSC NASA*	CS	August 1993
ESA ERS-2	ESA	ALT, SCAT, SAR, IR	1994+
RADARSAT	Canada NASA*	SAR	Late 1994
ADEOS	NASDA NASA*	SCAT, CS	1995

* Provides data or other services to U.S. research users.

ALT is radar altimeter

CNES is French space agency

CS is color scanner

ESA is European Space Agency

IR is infrared radiometer

OSC is Orbital Sciences Corporation

MR is microwave radiometer

NASA is National Aeronautics and Space Administration

NASDA is Japanese space agency

SAR is synthetic aperture radar

SCAT is scatterometer

USAF is United States Air Force

V Societal Implications

A. Introduction

The coastal ocean is by far the most subject to anthropogenic stress of all ocean regions. It is closest to ever-increasing human populations and represents a limited volume of water in which to absorb impacts. Stresses are likely to grow as world population grows and concentrates near the coast. Already there are well-publicized concerns about the health of the coastal ocean, including problems with garbage on beaches, oil spills, toxic blooms (Figure 16) and fisheries. Further, the coastal ocean is likely to be substantially affected by global change. For example, rises in sea level are likely to alter the shoreline and modify nearshore habitats. In addition, potential alterations of major storm patterns are likely to affect the shoreline, coastal organisms, and human activities.

The scientific results of CoOP will be useful in dealing with societal problems as well as purely scientific questions. It should be recognized that since CoOP plans to deal with issues related to the missions of a number of federal agencies, partnerships with these agencies are desirable. Discussions of societal needs are available elsewhere (e.g., Gulf of Mexico Program, 1990), so the following discussion is only a synopsis of some of the important practical problems related to the coastal environment, especially those on which CoOP is expected to have a long-term impact.

B. Pollution and Waste Management

Humanity has contributed various forms of pollution to the coastal ocean, ranging from agricultural fertilizer through sewage and garbage to toxic chemicals. These contaminants can enter the coastal ocean through dumping, the air, rivers or groundwater, making total inputs difficult to monitor and effects of particular pollutants and sources hard to isolate. Once contaminants enter the coastal ocean, they can be consumed by organisms, undergo chemical reactions and concentrate in animals and in sediments. Sensible decisions about controlling anthropogenic inputs depend on knowledge of transport of the material in question and whether natural processes disperse, transform or concentrate the impact. It has been generally impractical to regulate human activity to eliminate impact on the ocean, so it is desirable rather to manage the pollution so that it does no measurable harm. Further, we must consider the potential

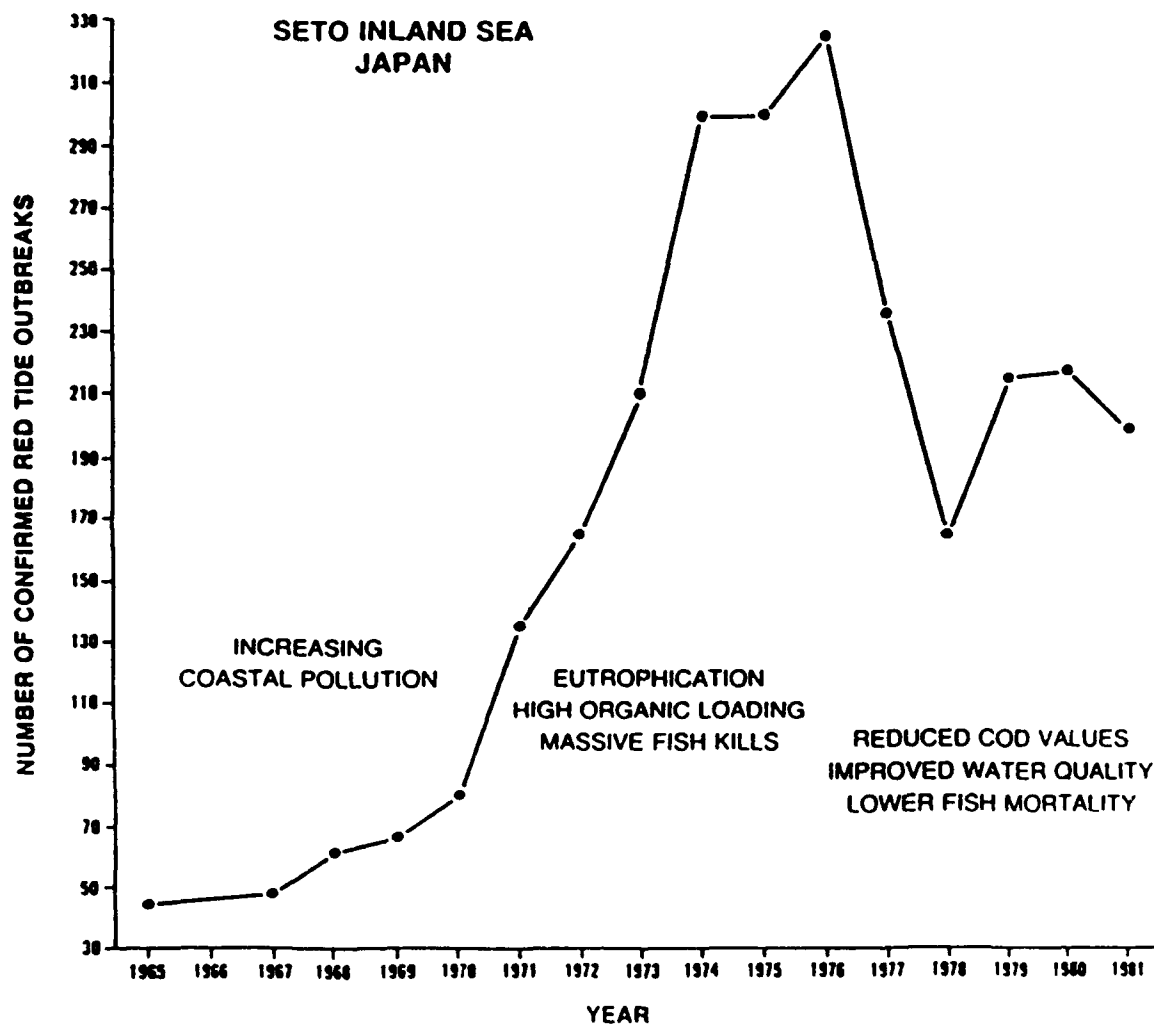


Figure 16: Trends in red-tide outbreaks from 1965–1981 in the Seto Inland Sea where the incidence of red tides is carefully monitored. From Smayda, 1990.

of the ocean for the disposal of wastes where they might do less harm than they would on the land or in the atmosphere. Making such choices requires knowledge of coastal winds, currents, mixing and chemical processes, as well of how the anthropogenic impact passes through the food chain and is expressed in the sediments. Such knowledge will be acquired through the meteorological, physical, biogeochemical and geological aspects of CoOP.

C. Mineral Exploitation

Historically, many minerals have been recovered from the coastal ocean (from mineral sands to concrete aggregate), but petroleum is now the most common mineral resource extracted. Concerns about the environmental safety of such exploitation have grown. Indeed, the Minerals Management Service (MMS) is being held to continually higher standards and a broader scope in terms of carrying out risk assessment for offshore drilling operations. Some of the issues of particular interest include estimating where oil spills are likely to go and the effects of drilling operations on ocean ecosystems and endangered species. Improving risk assessments, except perhaps involving endangered species, requires the same transport and transformation information as CoOP.

Science-related questions involved in offshore drilling are not limited to risk assessment. For example, engineers designing drilling structures need to have information about sea state and currents to create safe and economical designs. In addition, in the event of an oil spill, response teams need accurate information on where the oil will go. Both of these problems require an enhanced physical data base and modeling capability and CoOP will make major contributions on both accounts.

D. Navigation

Information about sea state, winds over the water, storms, visibility, and, to some extent, currents is valuable for navigation, whether it be commercial or recreational. Also, shipping often requires that channels be dredged in a manner that is economical and does not damage the environment. Finally, it would be valuable to have enough information about sediment transport to know where a channel could be located so as to minimize the need for future dredging. All of this information could be provided through advances in our understanding of coastal meteorology, currents and sediment

transport. CoOP studies focussing on air-sea exchanges and benthic-pelagic coupling are especially likely to be useful for these purposes.

E. Shore-based Recreation

The world's coasts are the site of a broad range of shore-based recreational activities. Coastal resorts attract visitors for swimming, fishing, wildlife observation and just generally enjoying the scenery. In many locations, the leisure industry is a major source of income for coastal communities. Problems such as beach erosion, pollution and toxic blooms can threaten the pleasure and income derived from such activities. Such essential problems are addressed in other sections such as Pollution and Waste Management (section V-B.) and Fisheries (section V-G.), but it is important to point out that these recreational uses of the coastal ocean have considerable economic importance in their own right.

F. Defense Needs

Because of recent international political events, defense planners are focussing on the coastal ocean as a site of possible future conflict. Surface ship, submarine and aircraft operations all require a detailed understanding of the coastal ocean and atmosphere. Typical requirements include: surf zone forecasting for amphibious operations and over-the-beach supply; knowledge of acoustic propagation for submarine and mine detection; atmospheric prediction for aircraft and missile deployment; and sediment transport for mine scour and burial. Nearly all warfare areas will benefit from increased fundamental knowledge of cross-shelf transport, air-sea interactions and benthic-pelagic couplings.

G. Fisheries

Commercial fisheries over the continental margin represent an important industry in the coastal states. The sustainability of the catch and the quality of the fish taken are major management issues. Related problems include habitat changes, anoxia, eutrophication and the increasing occurrence of toxic algal blooms and "nuisance species." Many of these issues are essentially questions of ecosystem dynamics. NOAA already has a major research enterprise to address the problems of this industry, and GLOBEC will tackle many ecosystem issues, so fisheries and the study of ichthyoplankton are not central to CoOP. Nonetheless, there appear to be many areas, particularly in the

realm of chemical and biological oceanography, where the CoOP interdisciplinary approach will complement or support fisheries investigations. CoOP will actively seek coordination with NOAA Fisheries and GLOBEC efforts, where appropriate, in order to optimize the use of resources and to enhance the scientific results obtained. CoOP studies involving cross-margin transport, terrestrial fluxes and biological transformations are likely to be especially relevant to fisheries issues.

H. Weather Prediction

Weather predictions over the ocean are sometimes difficult, partly for lack of data and partly because existing knowledge of air-sea interaction processes is not very complete. The coastal ocean has special features related to the presence of a coastal boundary and to the numerous types of thermal fronts that occur there. In addition, stable atmospheric boundary layers created by coastal upwelling create their own classes of interesting meteorological processes. All of these phenomena, while they enrich the subject scientifically, lead to complications for the weather forecaster. Because CoOP will make advances in coastal meteorology, it will contribute to a number of improvements in marine weather forecasting. For example, a better understanding of alongshore-propagating pressure systems will allow better prediction of fog, coastal cloudiness and precipitation.

I. Global Carbon Cycle

While the global carbon cycle is a scientific issue, it has become a societal concern because potential atmospheric warming and related changes in sea level, rainfall and other climate variables would have substantial economic impacts. The ocean is a major active reservoir of carbon, and the coastal ocean represents about 30% of global ocean primary productivity (Mantoura *et al.*, 1991) and 90% of global sedimentary accumulation of organic carbon (Berner, 1982). Carbon fixation and sedimentary accumulation are more likely to be affected by human activities in the coastal ocean than in the open ocean. Given these facts, the coastal ocean is a major part of the global carbon puzzle, and the processes that determine the uptake, transformation and removal of carbon in the coastal ocean take on global importance. CoOP, while not actually focussed on the carbon cycle, will make major contributions to this issue because biological processes, sedimentation and cross-shelf exchange are all highly relevant to the global carbon cycle. JGOFS and other research programs are studying the carbon cycle in

the remainder of the ocean, and it is important that CoOP coordinate efforts with such groups.

J. Coastal Hazards

Coastal hazards represent a broad set of problems associated with damage that the ocean can do to the landward side of the coastline. Examples include shoreline erosion and storm-induced flooding. NOAA carries out extensive studies directed at risk assessment and control of hazards. The improvements CoOP will make in coastal meteorology, sediment transport and nearshore oceanography will be of direct use to coastal hazard research. Once again, CoOP will seek opportunities to carry out synergistic research in coordination with applied scientists.

VI Conclusions

Most exploitable ocean resources are extracted from the continental margins, and most human impacts are concentrated in the coastal zone. Wise use of the ocean requires fundamental understanding of how the coastal ocean system operates. Recent advances in the tools available to marine scientists, including new measurement systems, computers and improved approaches of data analysis, have greatly enhanced our ability to investigate the complex processes of the coastal ocean. In particular, we are now equipped to study phenomena that are highly variable over a few hours of time and a few kilometers of space, and to combine our knowledge of small- and large-scale processes to yield quantitative understanding of the coastal ocean. Further, we have reached an intellectual stage where substantial advances require the major interdisciplinary efforts that can now be formulated based on existing information.

We have identified a goal that is central to improving fundamental understanding of the coastal ocean:

to obtain a new level of quantitative understanding of the processes that dominate the transports, transformations and fates of biologically, chemically and geologically important matter on the continental margins.

At present, we have substantial knowledge of currents and material transport in the along-shore direction. We have much poorer understanding of the cross-margin transports that link the land, coastal ocean and deep sea. The closely coupled question of air-sea exchange of materials and energy is also not well-understood. Quantification of these transports and exchanges is crucial to addressing many questions of both scientific and societal importance, including: How do the atmosphere and ocean interact to produce coastal weather? What sources of nutrients support high levels of productivity in the coastal ocean? How do transport processes affect the structure and productivity of coastal ecosystems? Is organic matter produced over continental margins exported to the deep ocean or buried in sediments? Do coastal ocean processes have a significant role in the global exchange of carbon dioxide between the atmosphere and the ocean? Are significant amounts of terrestrially-derived materials, including pollutants, transported across the margin to the deep sea, or is the margin an efficient "trap" for such materials?

Many continental margins are at present characterized with regard to their general properties, but oceanographers have little ability to understand or predict phenomena at one location based on knowledge of another. Our very limited understanding of cross-margin transport of materials requires intensive, interdisciplinary studies of selected coastal regions. These regions will be chosen on the basis of key processes that are important to the transport and transformation of materials in many coastal regions. The ultimate goal is to develop unifying, quantitative descriptions of coastal ocean phenomena that can yield a general understanding of material transport on continental margins.

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Glossary of Technical Terms

Adsorption: Sticking to a surface.

Advection: Transport by the net motion of a fluid such as air or water.

Aeolian: Carried by winds.

Albedo: The tendency of a body to reflect sunlight and radiative heat.

Analytical model: A model of a process sufficiently simple to allow mathematical or algebraic expressions for the results.

Anoxia: The absence of dissolved oxygen from the water.

Atmospheric inversion: The gravitationally stable layer at the top of the atmosphere's turbulent boundary layer.

Benthic: Of or pertaining to the sea floor.

Bioirrigation: The movement of fluids through pore spaces of the seabed as the result of biological activities.

Biological pump: The suite of biological processes affecting the rates at which carbon dioxide and nutrient salts are removed from the surface mixed layer and vertically transported through the water column to the sediments.

Bioturbation: The displacement of sediment particles within the seabed as the result of biological activities.

Bolus: A separated body of water with properties distinct from the surrounding water.

Boundary layer: A region of a fluid (such as the ocean or atmosphere), thin compared to the rest of the volume, that contains special processes, such as the high turbulence within an Ekman layer.

Colloids: Very fine particulate material (finer than $\sim 0.5 \mu$) kept in suspension by Brownian movement.

Cyanobacteria: A class of very small photosynthetic organisms prevalent in oligotrophic waters.

Desorption: The release of changed chemical species from the surfaces of particles.

Detritus: Waste products and dead organisms.

Diel: Occurring on a 24-hour cycle.

Ekman transport: The horizontal mean motion of water within a boundary layer influenced by turbulence and the earth's rotation. This can occur either in the atmosphere (in a layer typically 100–1000 m thick) or in the ocean (in a layer typically 10–100 m thick).

Epibenthic: Living above the sediment, that is, directly on the bottom.

Euphotic zone: That portion of the upper ocean having sufficient sunlight to sustain net photosynthesis.

Eutrophication: Enhanced input of nutrients from sewage, agriculture or air–sea exchange.

Extratropical cyclones: Major storms not originating in equatorial regions.

Fecal pellets: Aggregates of particulate material defecated by marine organisms and exhibiting strong adhesive character from mucous secretions.

Flocculation (or coagulation): The process by which discrete particles in seawater form larger aggregates as the result of electrostatic forces on particle surfaces.

Fluvial: Having to do with rivers.

Fronts: Sharp horizontal boundaries in air or water properties.

Geostrophic: Flow generally occurring at the larger space and time scales where pressure gradients balance the Coriolis force associated with the earth's rotation.

GLOBEC: Global Ocean Ecosystem Dynamics

Ichthyoplankton: Larval fish incapable of moving against currents.

Infauna: Animals living in the sediments.

Internal waves: Perturbations in the ocean or atmosphere (analogous to the familiar surface waves observed at beaches) that propagate along density interfaces within a fluid.

Interstitial: Situated between sediment particles as in water or organisms.

Intertidal region: That portion of the seabed beneath seawater at high tide and exposed during low tide.

Isobaths: Contours of constant water depth.

JGOFS: Joint Global Ocean Flux Study

Karstic topography: Irregular relief resulting from dissolution of limestone rocks.

Labile: Readily mineralized to inorganic constituents.

Mesoscale: In the atmosphere, ranging in size from about 10 to 300 km.

Microbial: Pertaining to microbial (bacterial) organisms.

NASA: National Aeronautics and Space Administration.

Nepheloid: Cloudy or turbid due to suspended particles.

New production: That portion of primary production supported by nutrients that have not been "recently" recycled, where "recently" generally refers to time scales much longer than 1 day.

NOAA: National Oceanic and Atmospheric Administration

NSF: National Science Foundation

Oligotrophic: Refers to waters having low concentrations of nutrients and organisms.

Pelagic: Refers to the upper few hundred meters of the water column.

Phytoplankton: Single-celled photosynthetic organisms.

Plankton: Small living things unable to maintain themselves against the movement of water.

Primary productivity: Amount of photosynthetically-fixed carbon per unit water volume or sea surface area per unit time.

Productivity: Amount of carbon produced by a specified class of organisms or trophic level (e.g., phytoplankton, zooplankton, primary, secondary) per unit water volume or sea surface area per unit time.

Prognostic model: A numerical model that uses forcing functions to predict the response to these forcing functions. This is as opposed to a diagnostic model, which fixes some aspects of the response (normally the temperature and salinity fields for ocean circulation models) in order to understand the system behavior consistent with the forcing and fixed aspects of the response.

Radiation: In the context of this report, referring to light or heat, not to anything that would endanger life.

Recruitment: For fisheries, the entering of a species into a harvestable stage.

Remineralization: Diagenetic change of chemical species, often release from solid phase to dissolved phase.

Solutes: Chemical species found within seawater in the dissolved phase.

Stability: A system state that will not change radically when perturbed, or a measure of this tendency. Most often, this refers to the density stratification of a fluid column. Dense fluid over light fluid is gravitationally unstable (it will overturn), but light fluid over dense is gravitationally stable (it will not change if perturbed).

Stratiform: Consisting of horizontal layers.

Subeuphotic: Below the euphotic zone, generally taken to mean where light is 1% or less of the surface value.

Synoptic scale: In the atmosphere, sizes ranging from about 10 to 300 km.

Taxonomic: The division of biological organisms into various named categories (e.g., genus, species, etc.) based on form and shape of the organisms.

Tectonic: Referring to large-scale processes that move the earth's crust horizontally (sea floor spreading) and vertically (mountain building).

Thermohaline: Having to do with the temperature and/or salinity of the ocean.

Trophic Levels: Groups of organisms defined by feeding preferences.

WOCE: World Ocean Circulation Experiment.

UNOLS: University-National Oceanographic Laboratory System.

Zooplankton: Small animals that are part of the plankton.

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16. Abstract (Limit: 200 words) CoOP (Coastal Ocean Processes) is an organization meant to study major interdisciplinary scientific problems in the coastal ocean. Its goal is "to obtain a new level of quantitative understanding of the processes that dominate the transformations, transports and fates of biologically, chemically and geologically important matter on the continental margin". Central to obtaining this understanding will be advances in observing and modeling the cross-shelf component of transport. More specific objectives are to understand 1) cross-margin exchanges, 2) air sea exchanges, 3) benthic-pelagic exchanges, 4) terrestrial inputs and 5) biological and chemical transformations within the water column. CoOP research will be carried out primarily through a series of process-oriented field studies, each involving about two years of measurements. Each of these field studies is to be initiated and defined through a community workshop. In addition to the process studies, CoOP will also involve modeling, long time series, exploratory studies, remote sensing, technological innovation, data archiving and communications. A CoOP pilot study has been approved for funding by the National Science Foundation, and funding will begin in 1992. The CoOP science effort is thus already underway.			
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